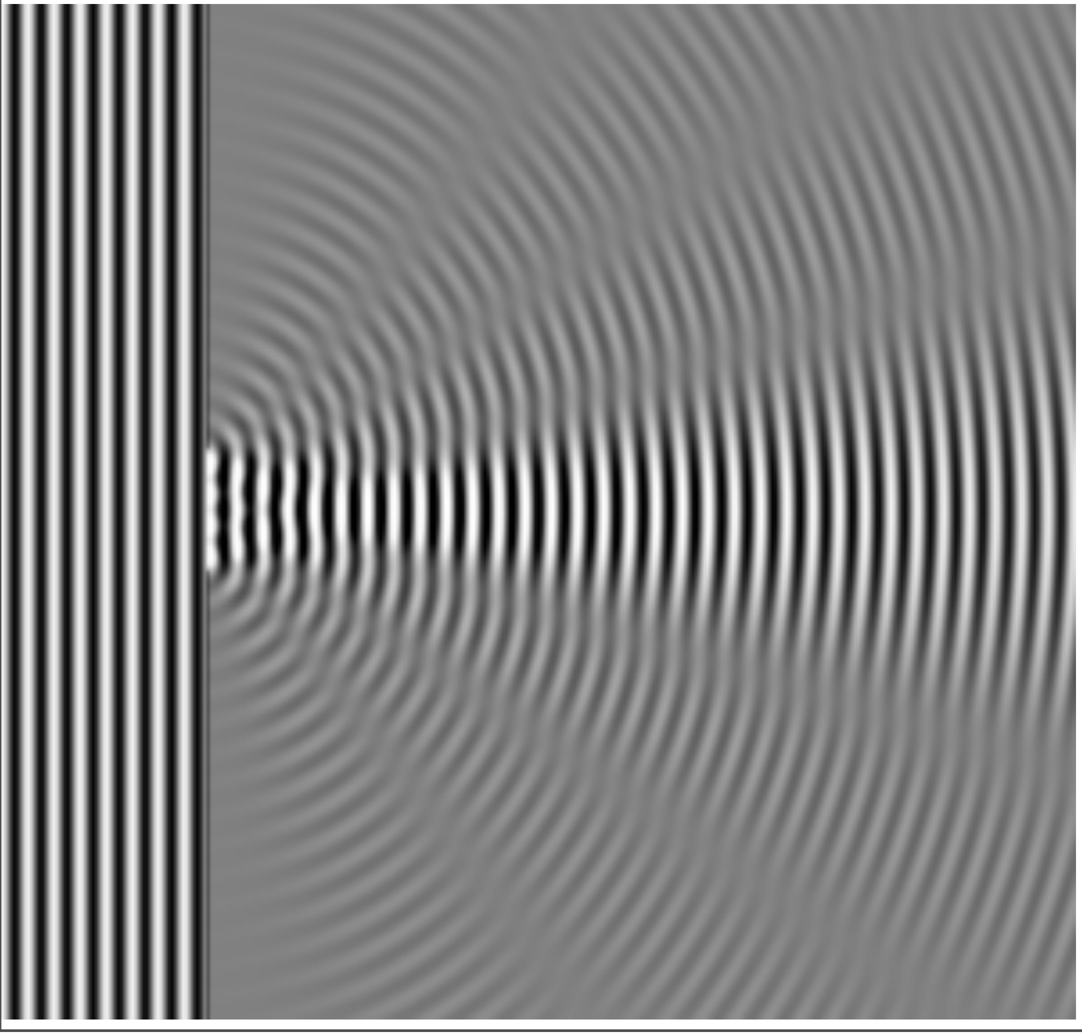
BROOKHAVEN NATIONAL LABORATORY

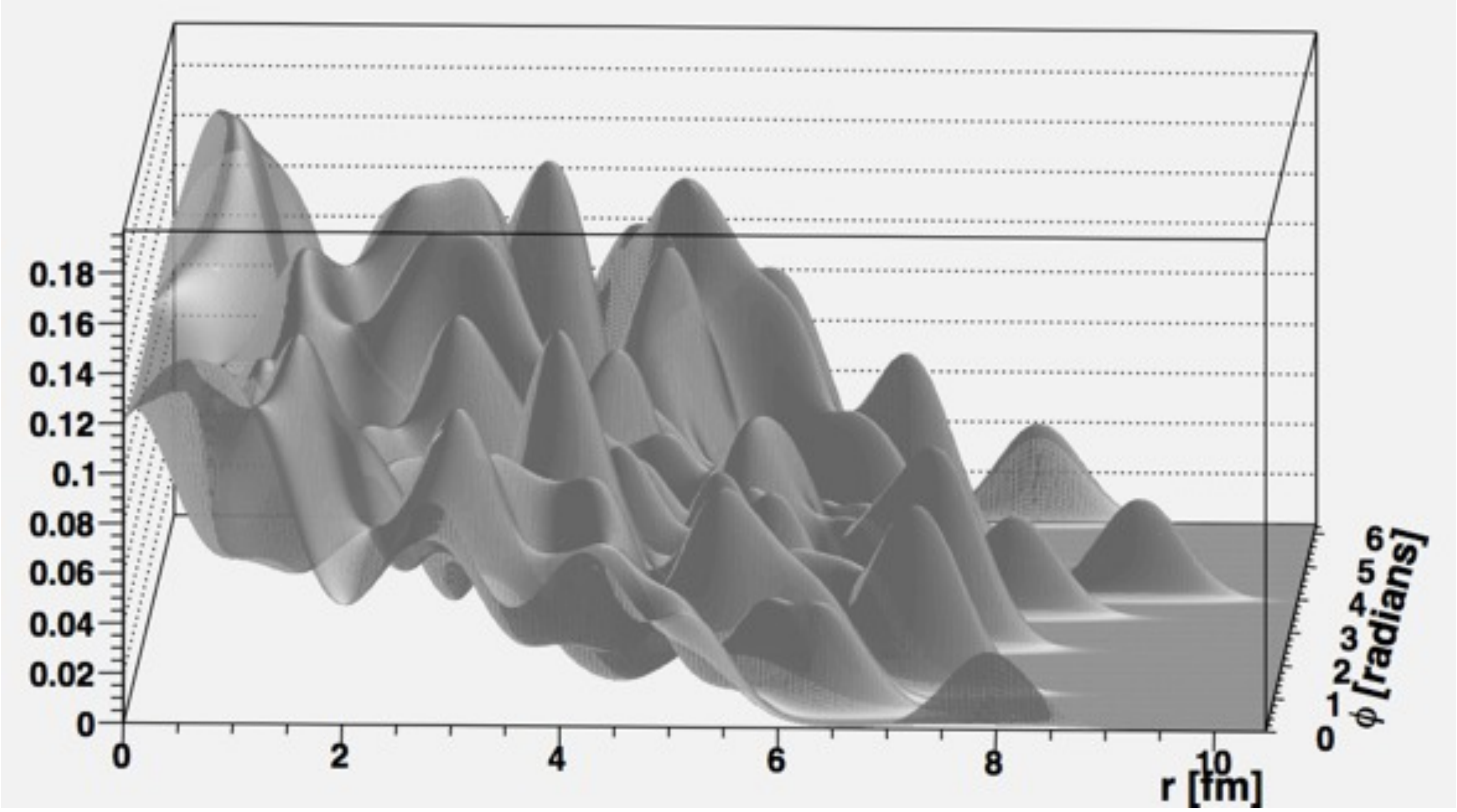
eRHIC

Understanding the initial condition of the heavy ion

2012 RHIC & AGS Annual Users' Meeting

Tobias Toll





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Our understanding of some fundamental properties of the Glasma, sQGP and Hadron Gas depend strongly on our knowledge of the initial state!

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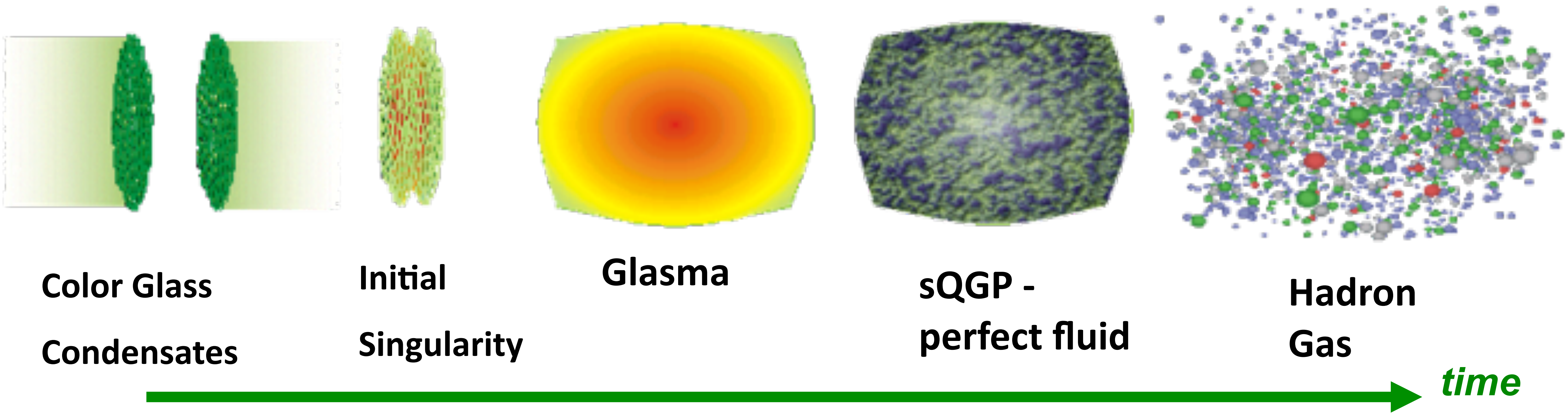

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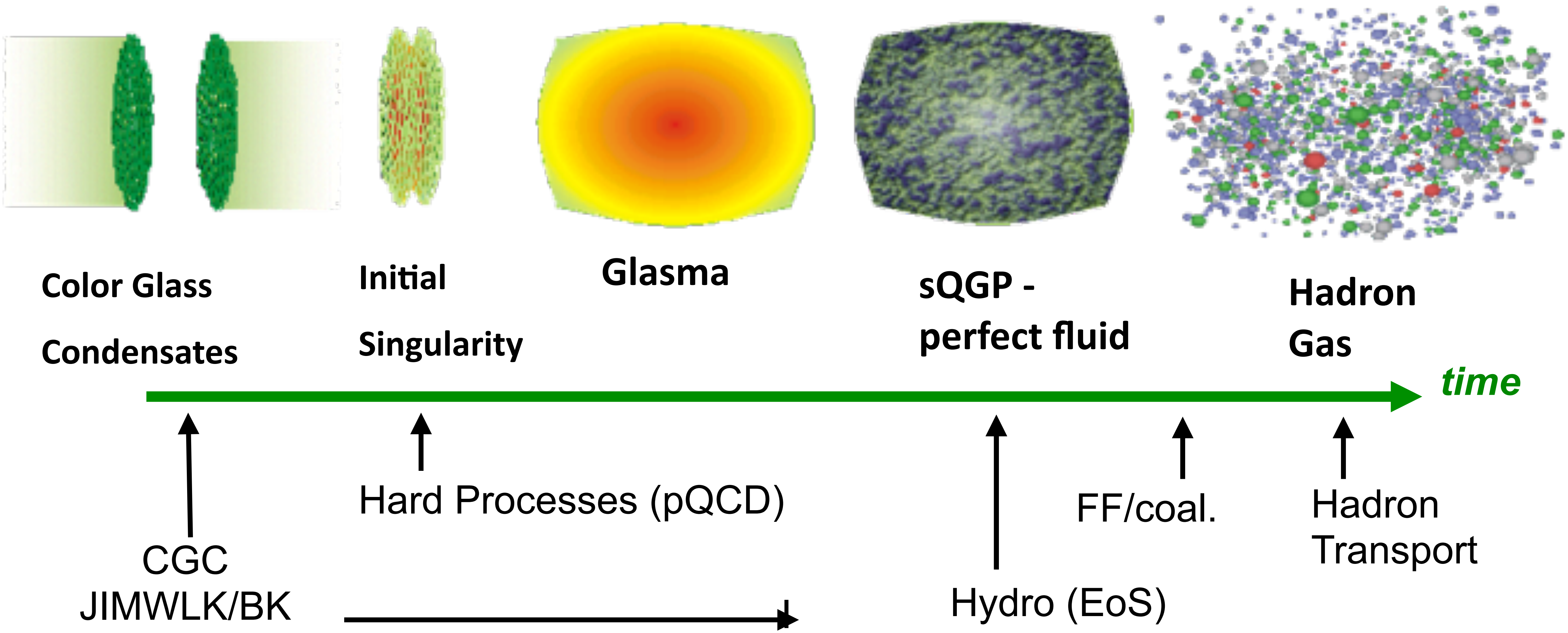

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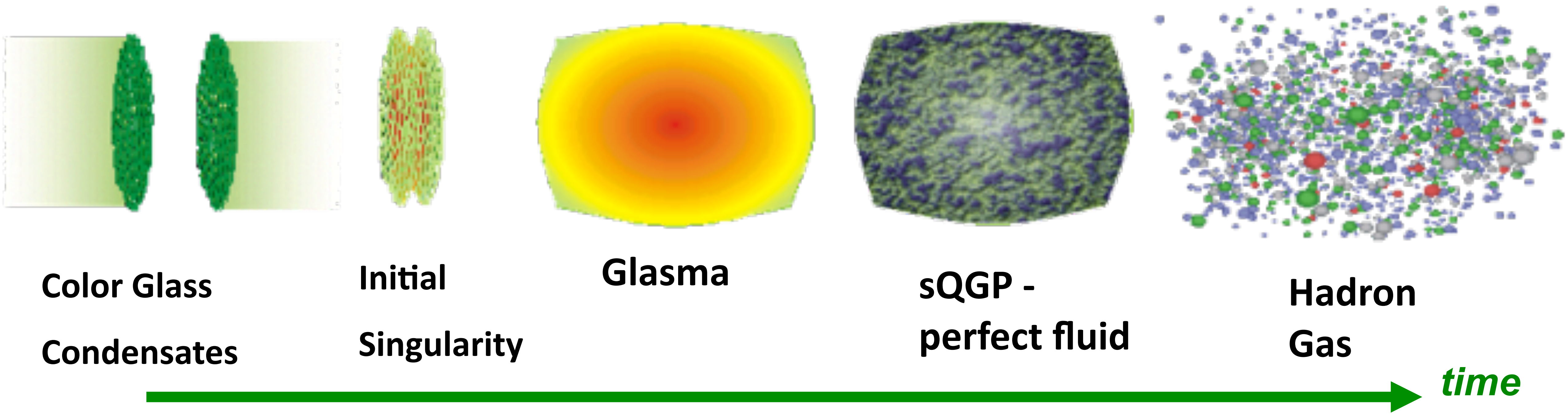

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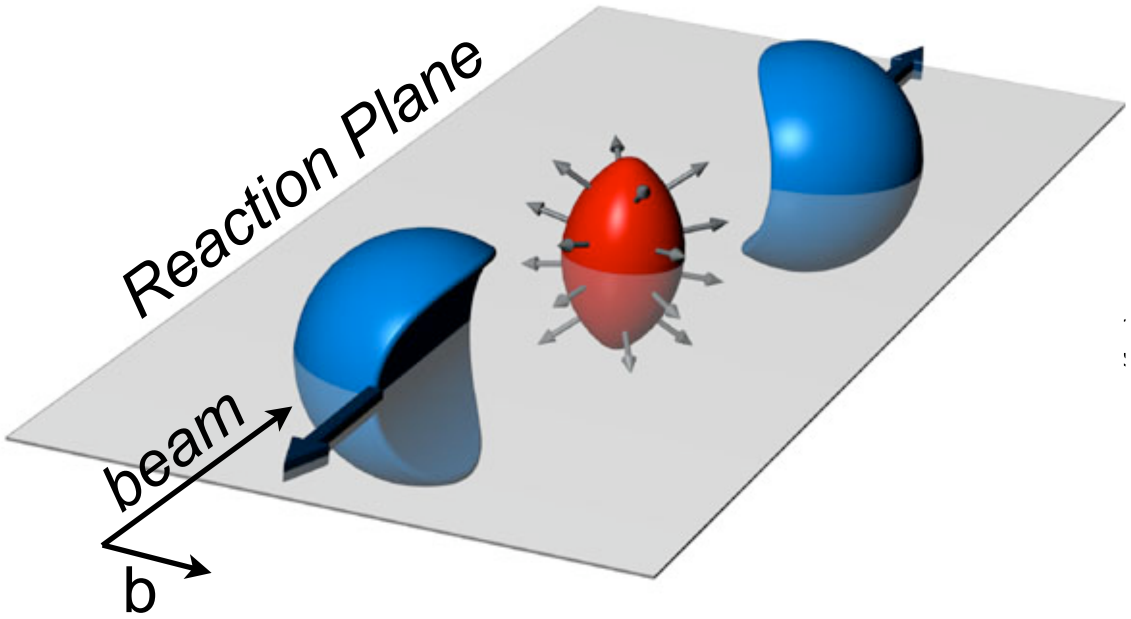

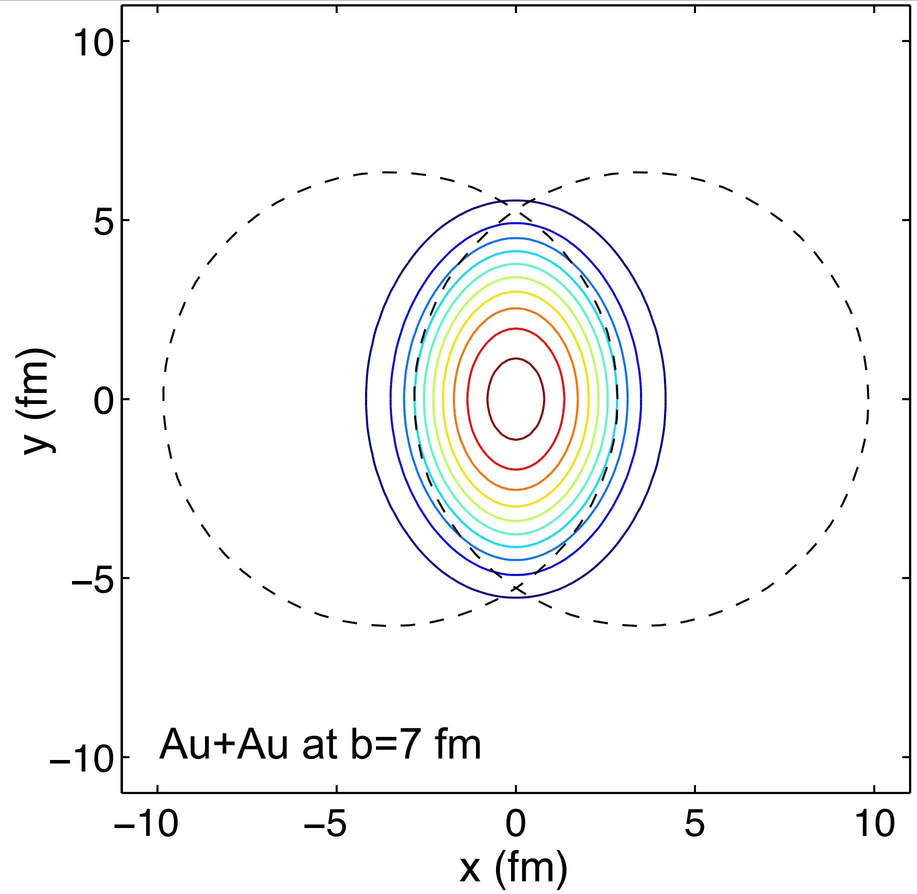

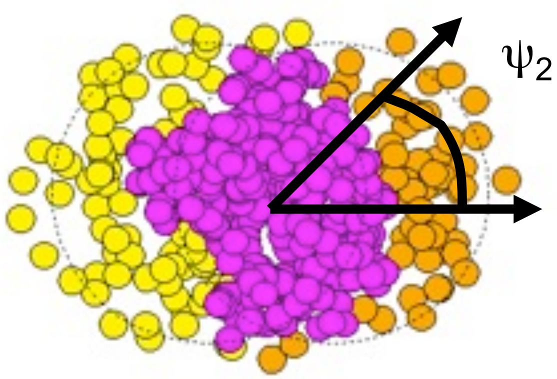

$$\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)] + \ldots$$

$$v_2 = \langle \cos[2(\varphi - \psi_R)] \rangle$$

Sensitive to early interactions and pressure gradients

In ideal hydrodynamics $v_2 \propto$ spatial eccentricity ε_2: $\epsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$

v_2/ε versus particle density is sensitive test of ideal hydrodynamic:

$$\frac{v_2}{\epsilon_2} = \frac{h}{1 + B / \left(\frac{1}{S} \frac{\mathrm{d}N}{\mathrm{d}y} \right)}$$

S= transverse area,

h = hydro limit of v_2/ε and B $\propto$ η/s

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Different initial distributions gives different flows!

Two methods for ε:

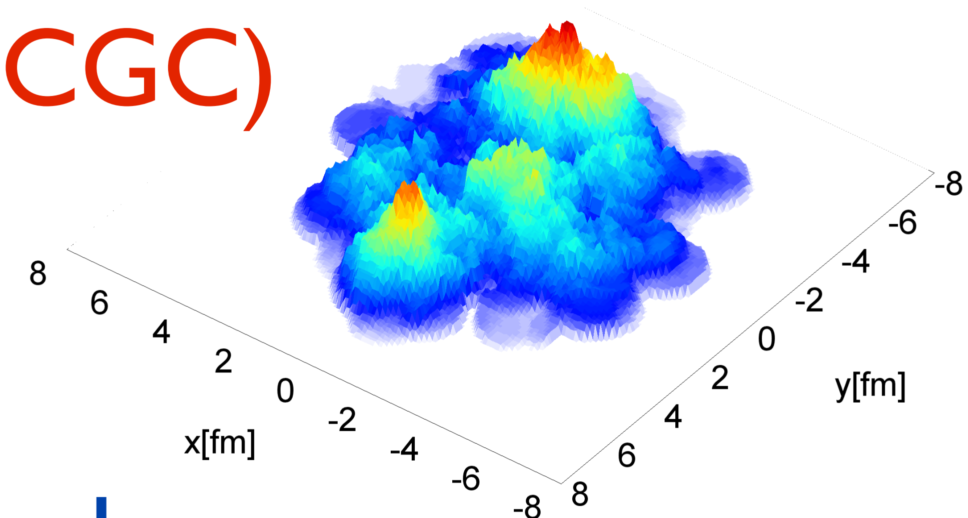
- Glauber (non-saturated)?
- CGC (saturated)?

The question is what is ε?

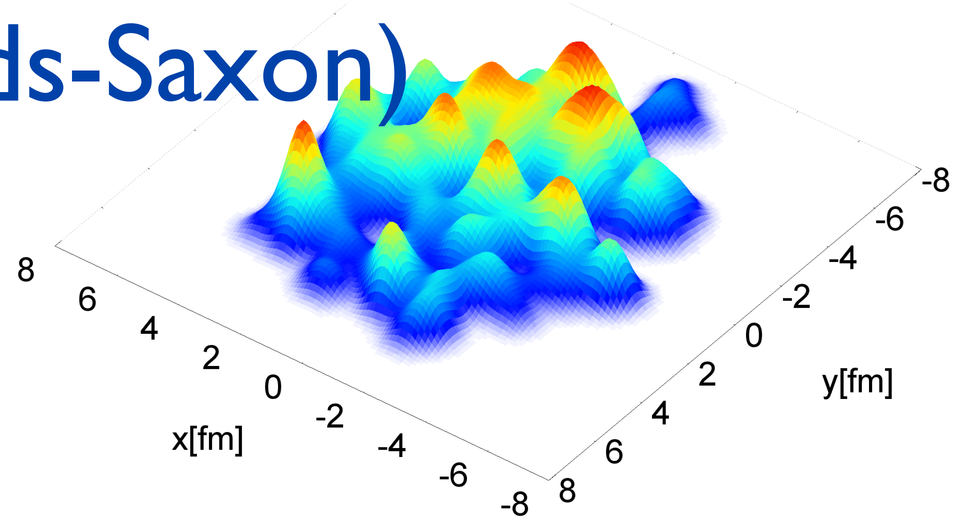
RHIC & LHC: low-p_T realm driven almost entirely by glue

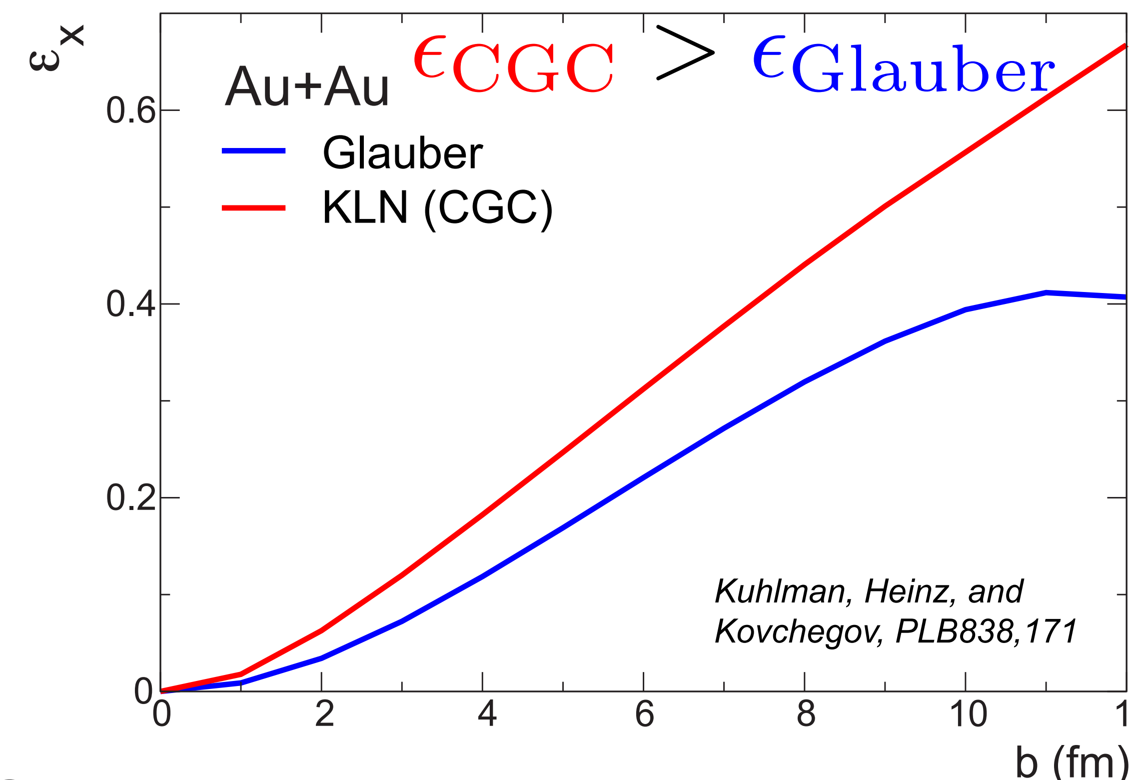
⇒ spatial distribution of glue in nuclei?

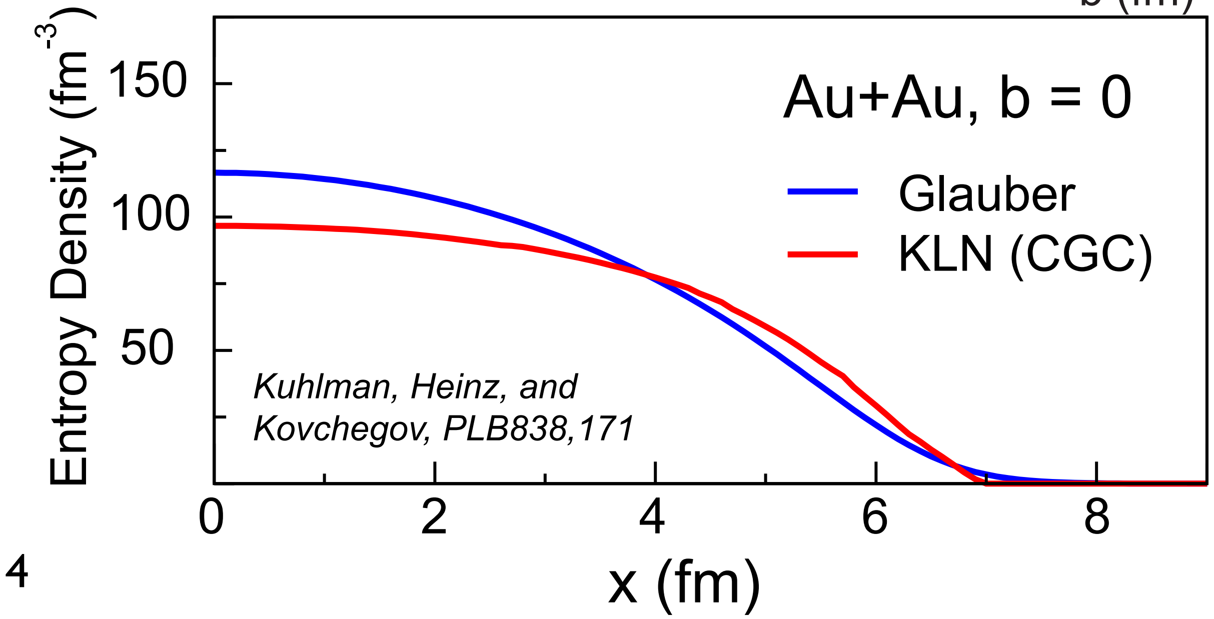
KLN(CGC)



Glauber (Woods-Saxon)







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Impact on η/s

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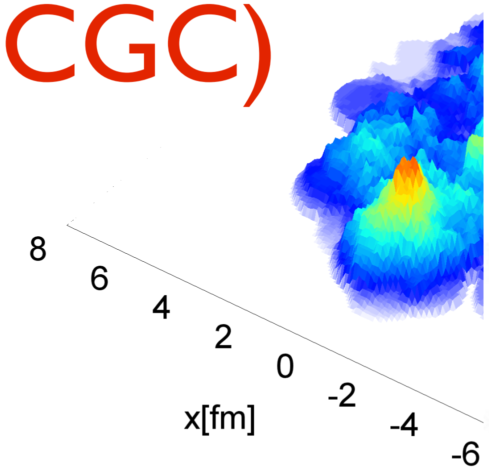

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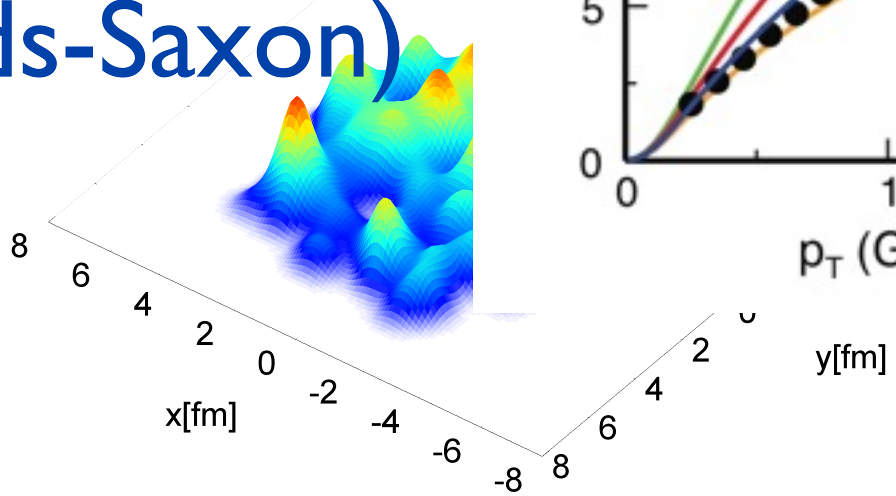
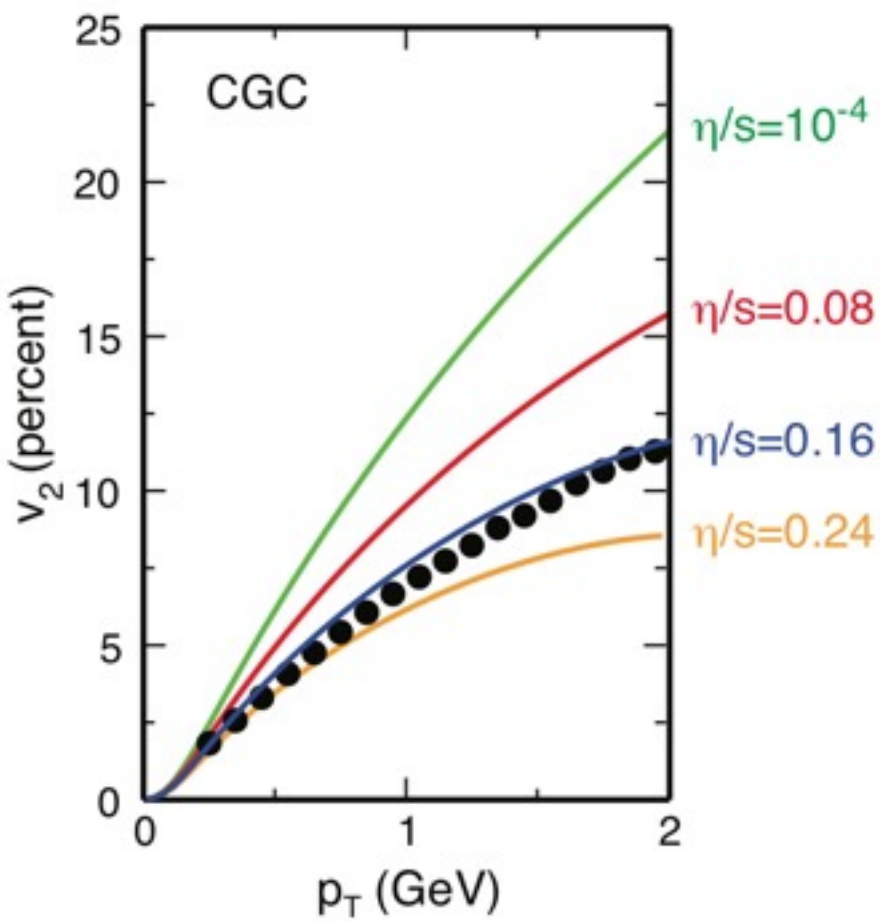
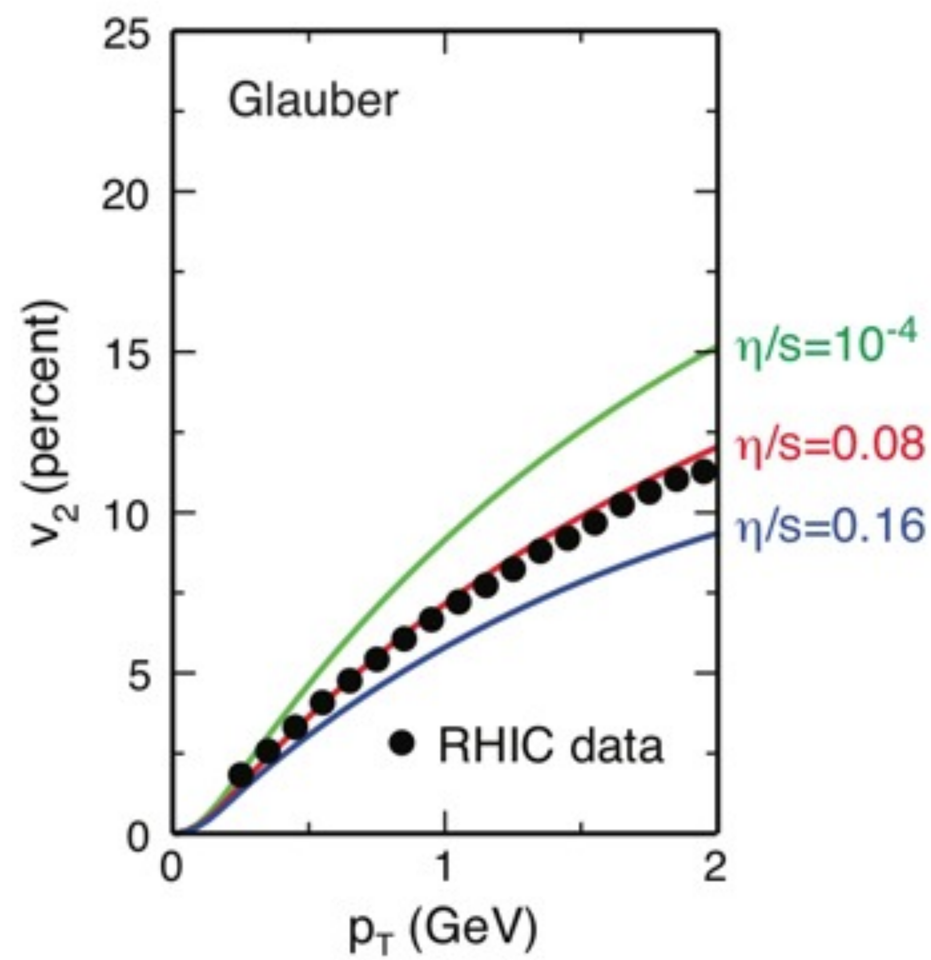
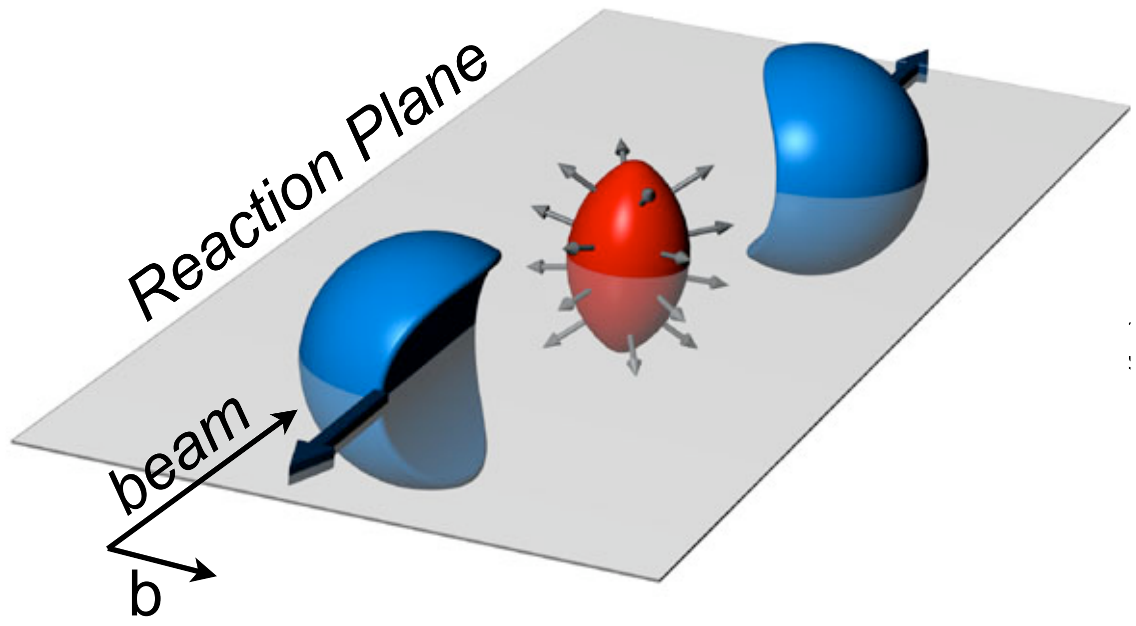
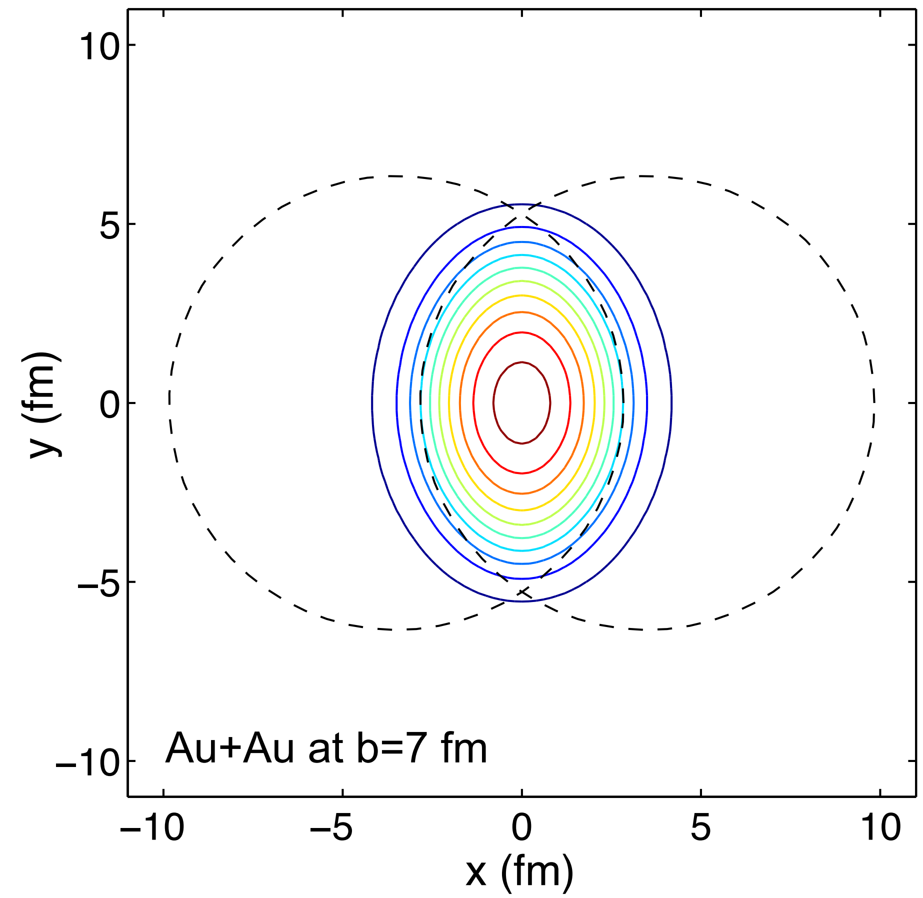
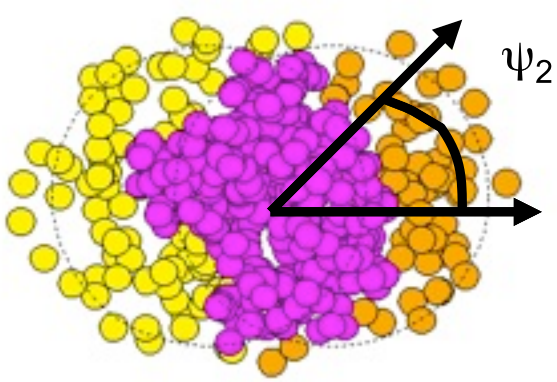




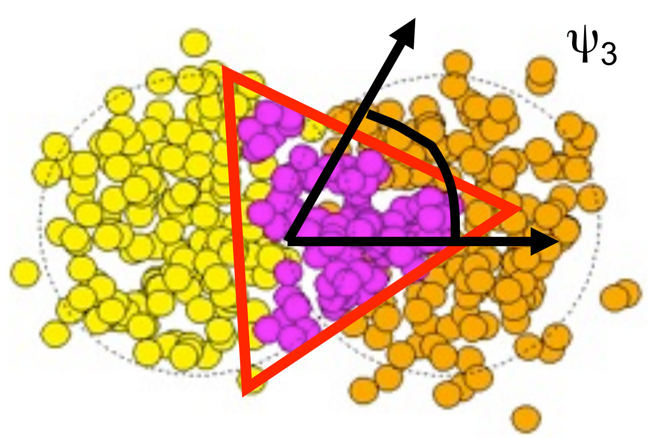






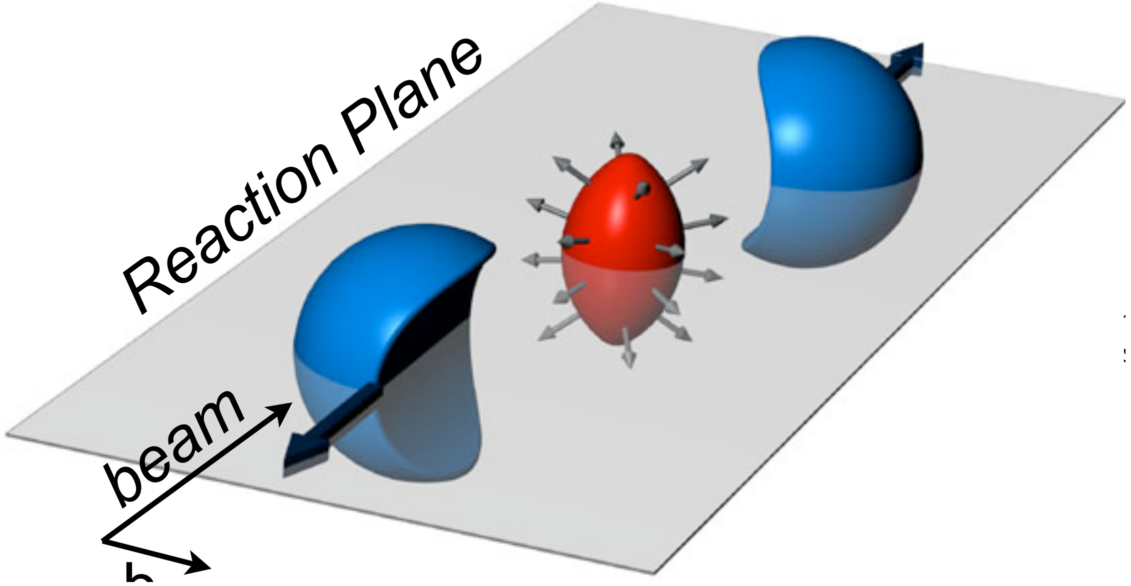


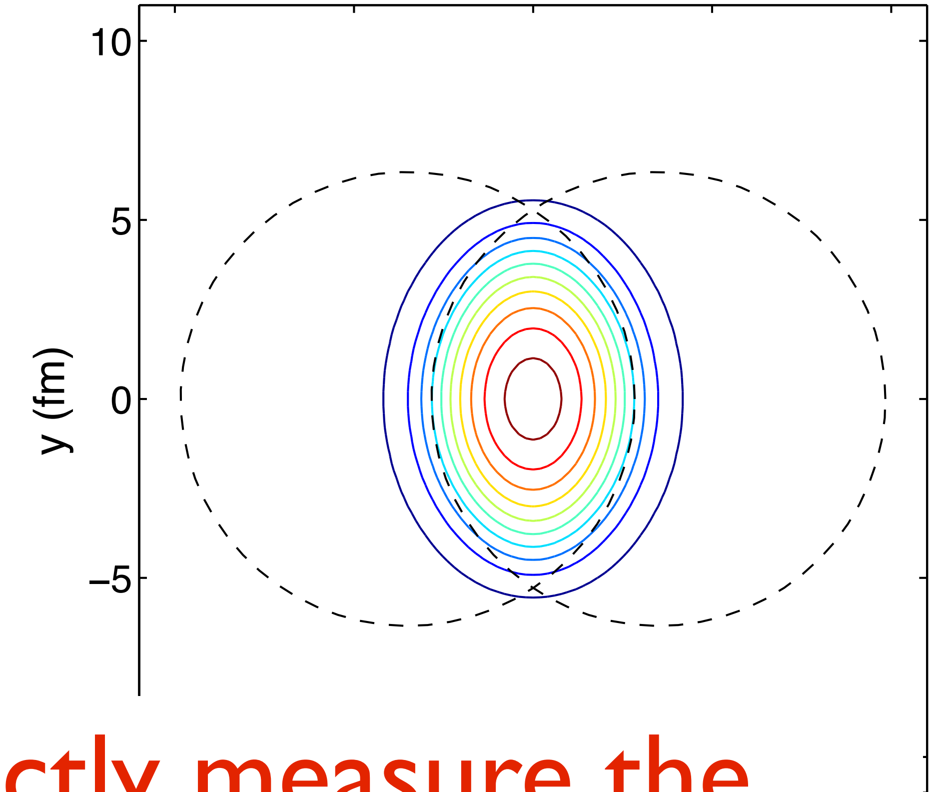
$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\psi_n)\rangle^2 + \langle r^n \sin(n\psi_n)\rangle^2}}{\langle r^n \rangle}$$



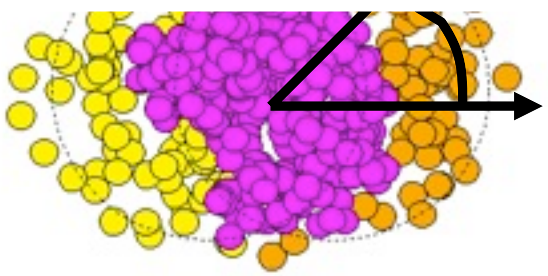
ε_2 and v_2 depend on ion density distribution

ε_3 and v_3 depend also on fluctuations!





Would be great to directly measure the transverse structure of the ion!



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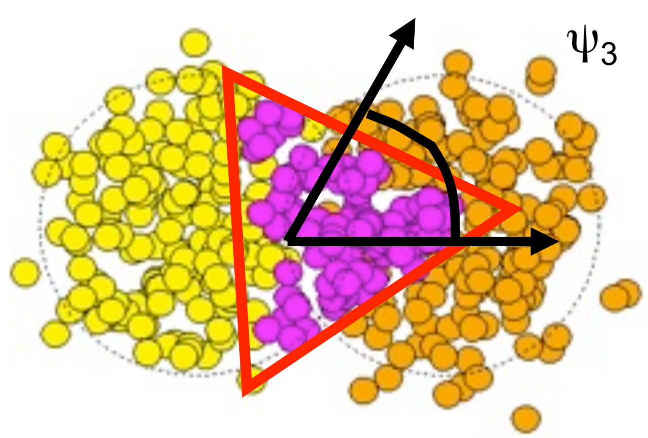

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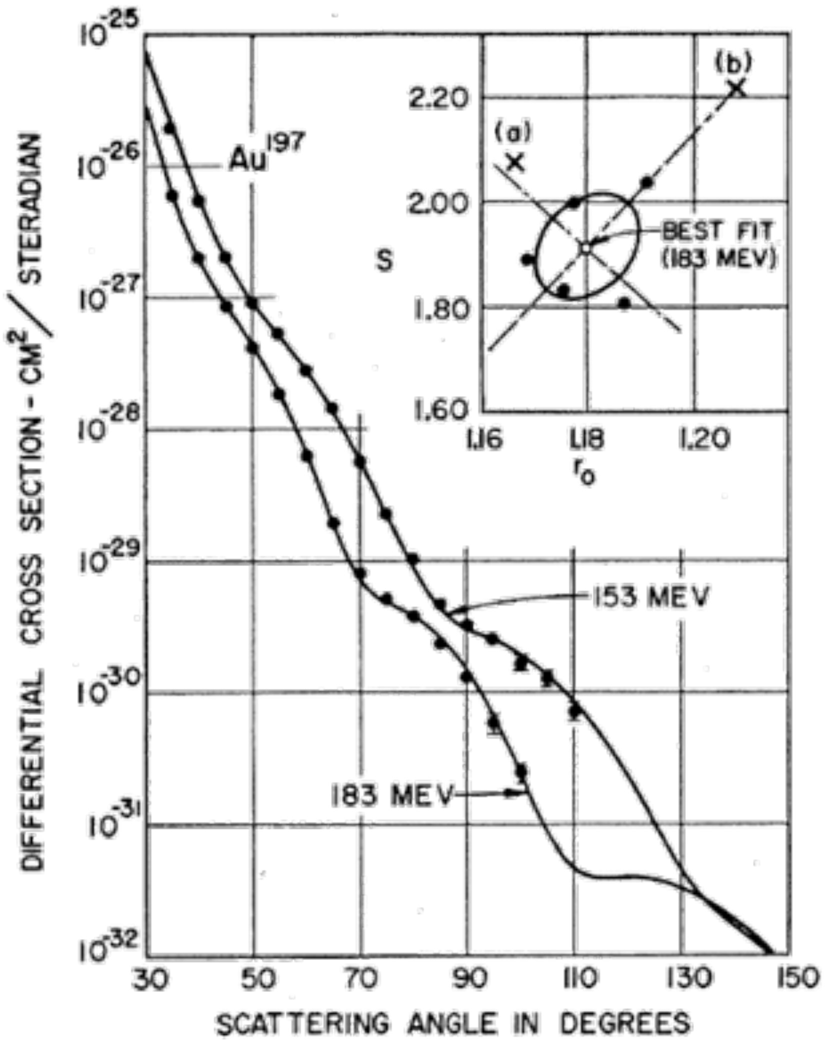
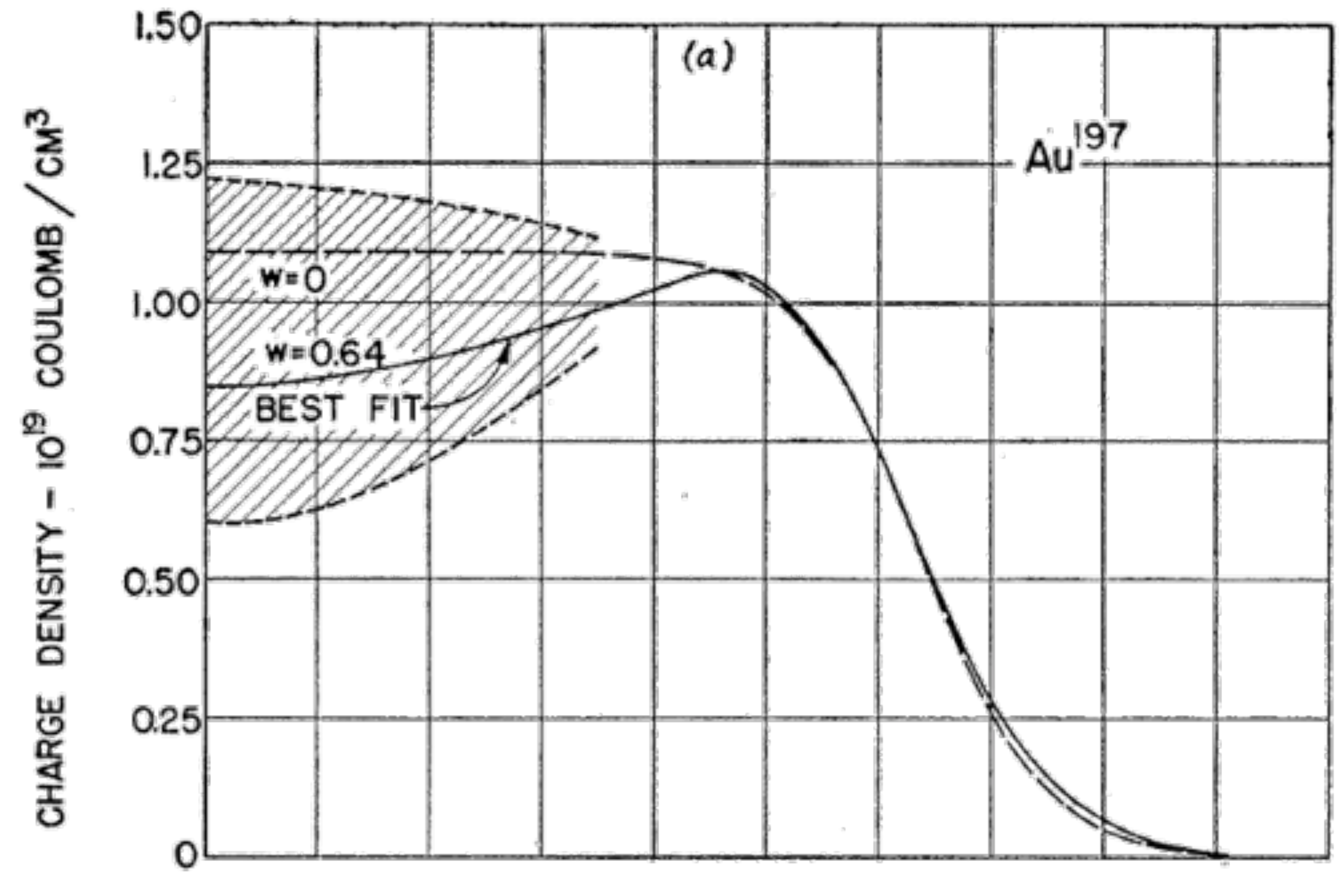
What exists?

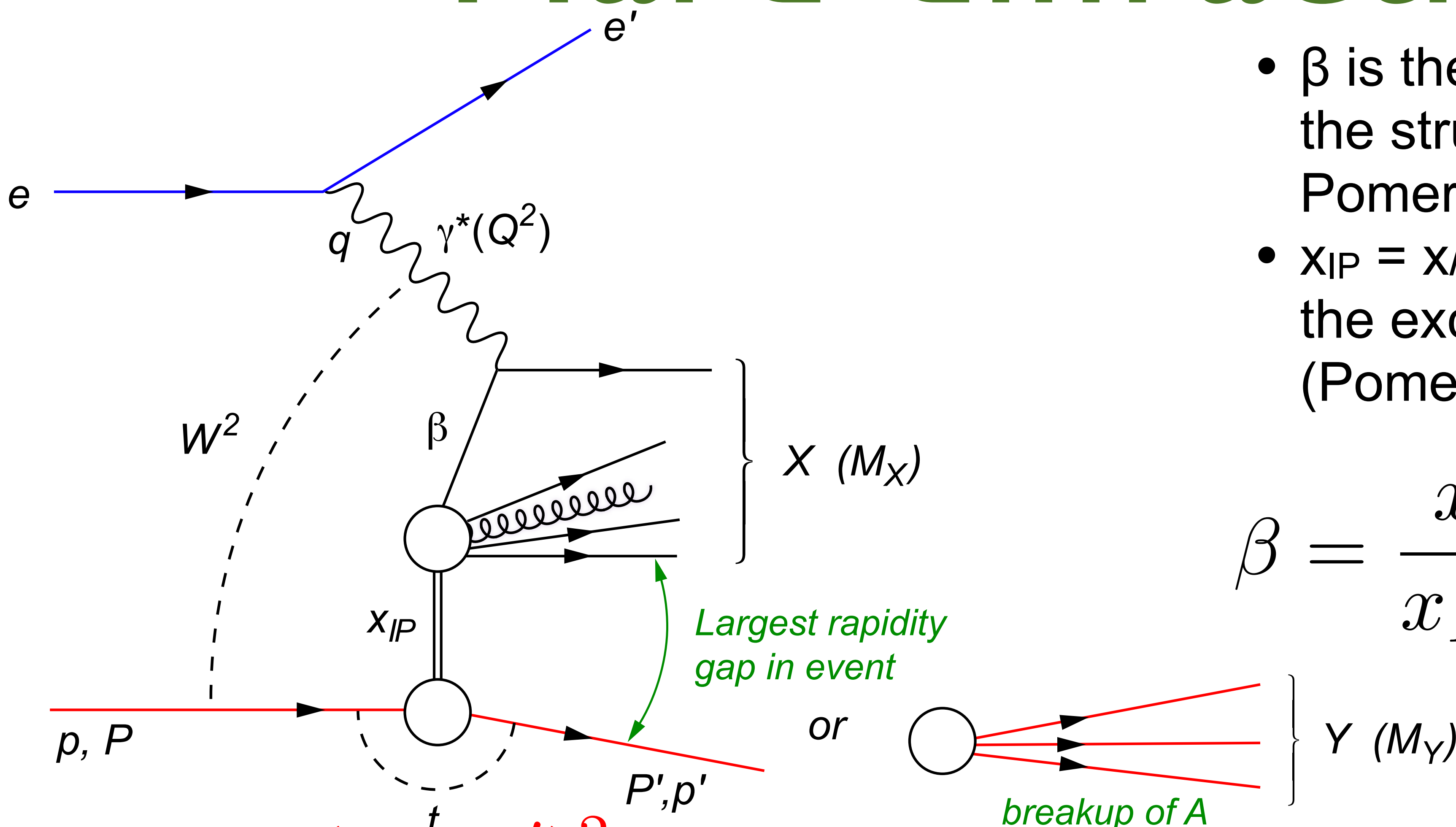




Hahn, Ravenhall, and Hofstadter,
Phys Rev 101 (1956)

Electron colliding with fixed ion target, large *x* charge distribution

Hard diffraction



$$t = (p - p')^2$$

- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

$$\beta = \frac{x}{x_{I\!P}} = \frac{Q^2}{Q^2 + M_X^2 - t}$$

- **Diffraction in e+p:**
  - HERA: 15% of all events are diffractive
- **Diffraction in e+A:**
  - Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%
  - Coherent diffraction (nuclei intact)
  - Incoherent diffraction: breakup into nucleons (nucleons intact)

Hard diffraction

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Why is diffraction so great?

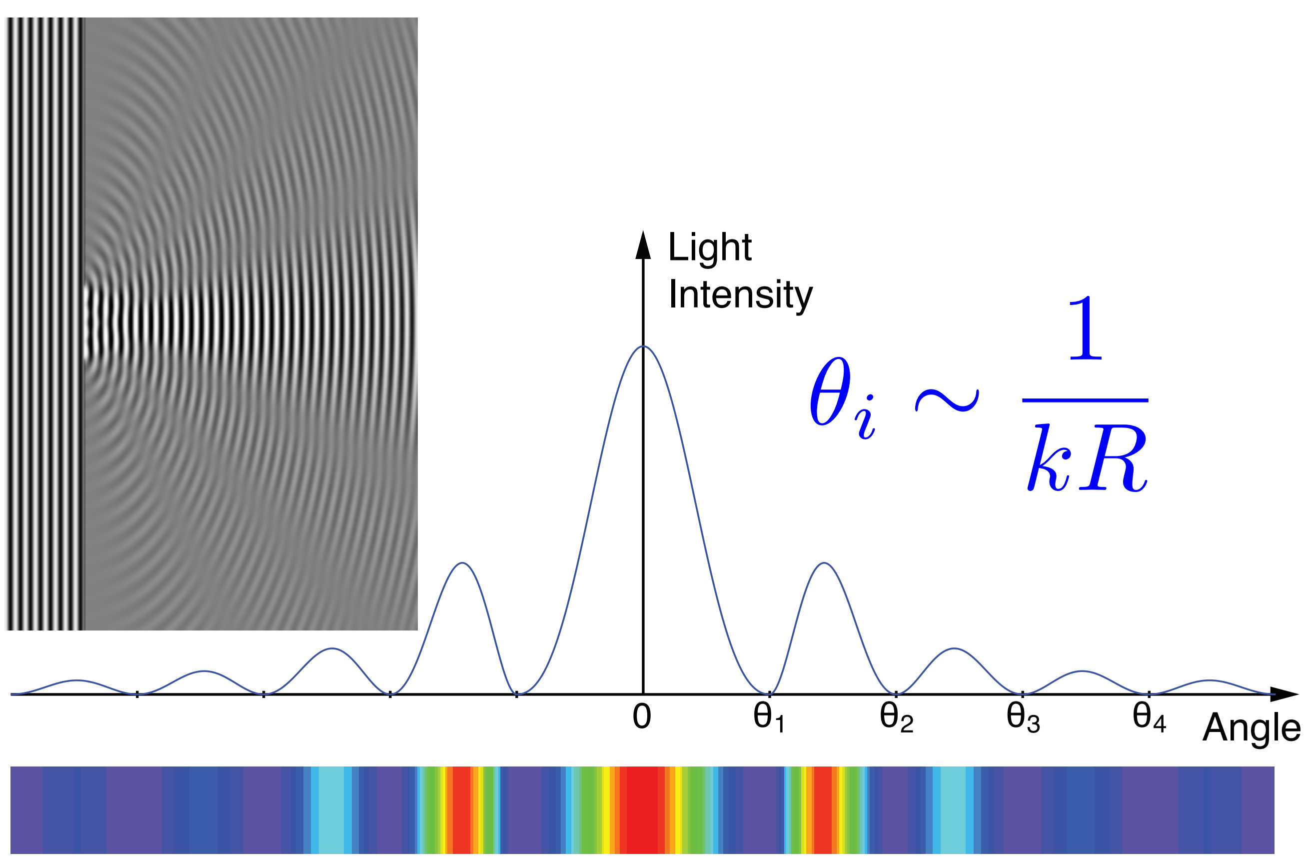
Sensitive to spatial gluon distributions

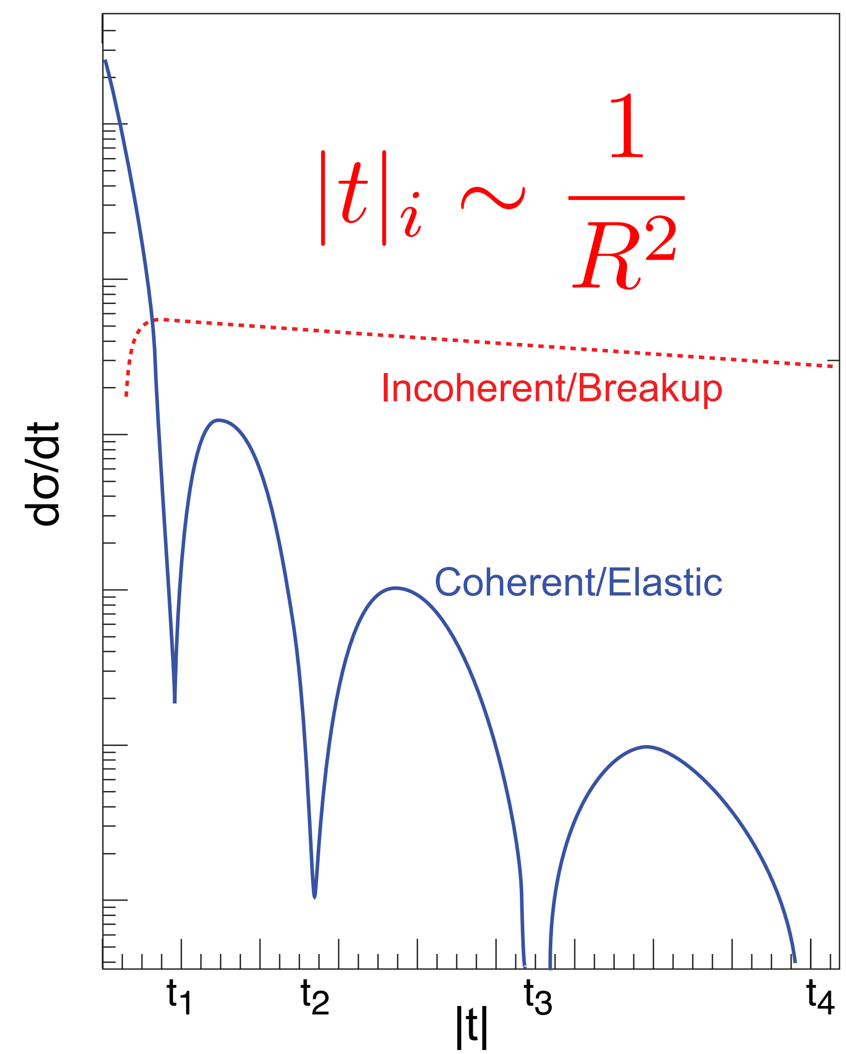
Light scattering off a circular screen of radius R

A projectile scattering off a nucleus of radius R

-not a 'black disk', edge effects

-target may break up





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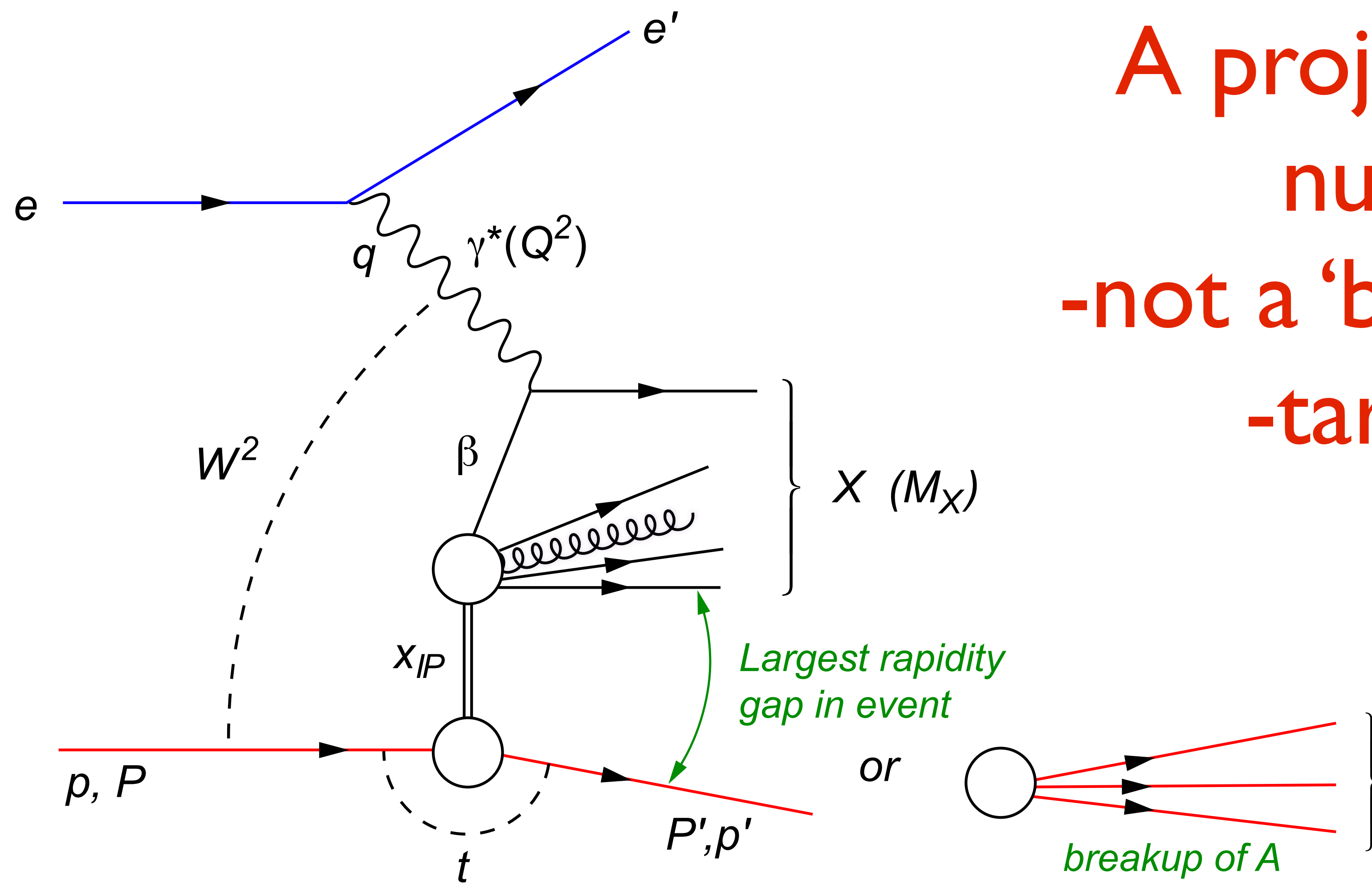

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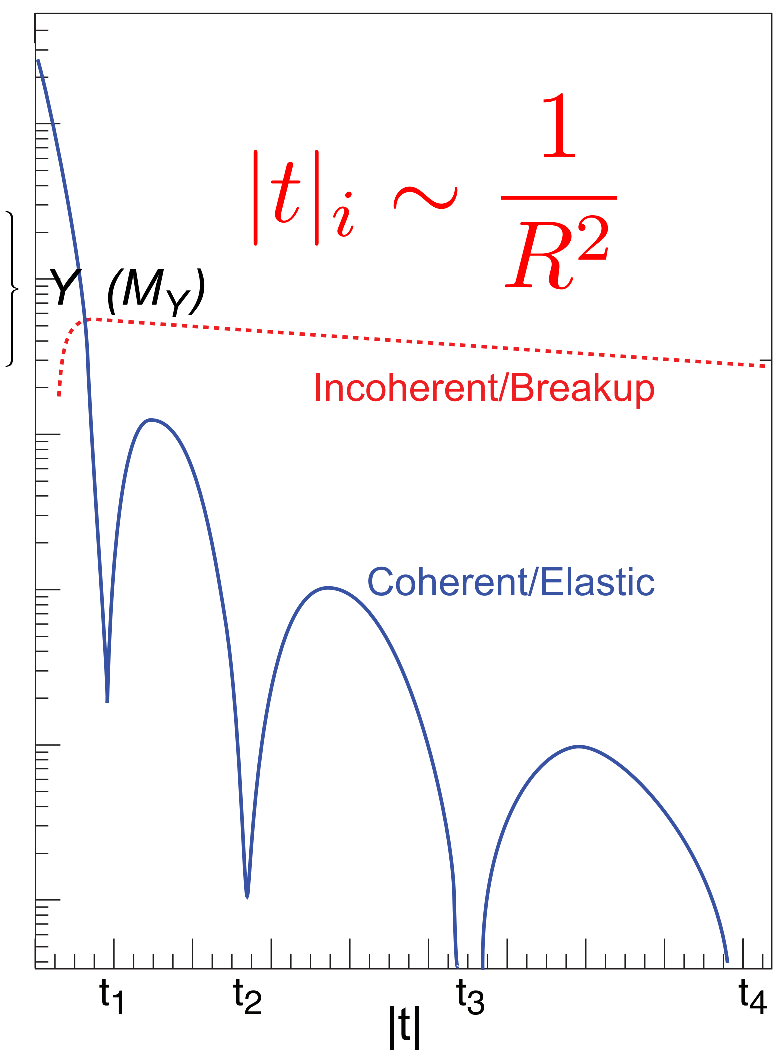

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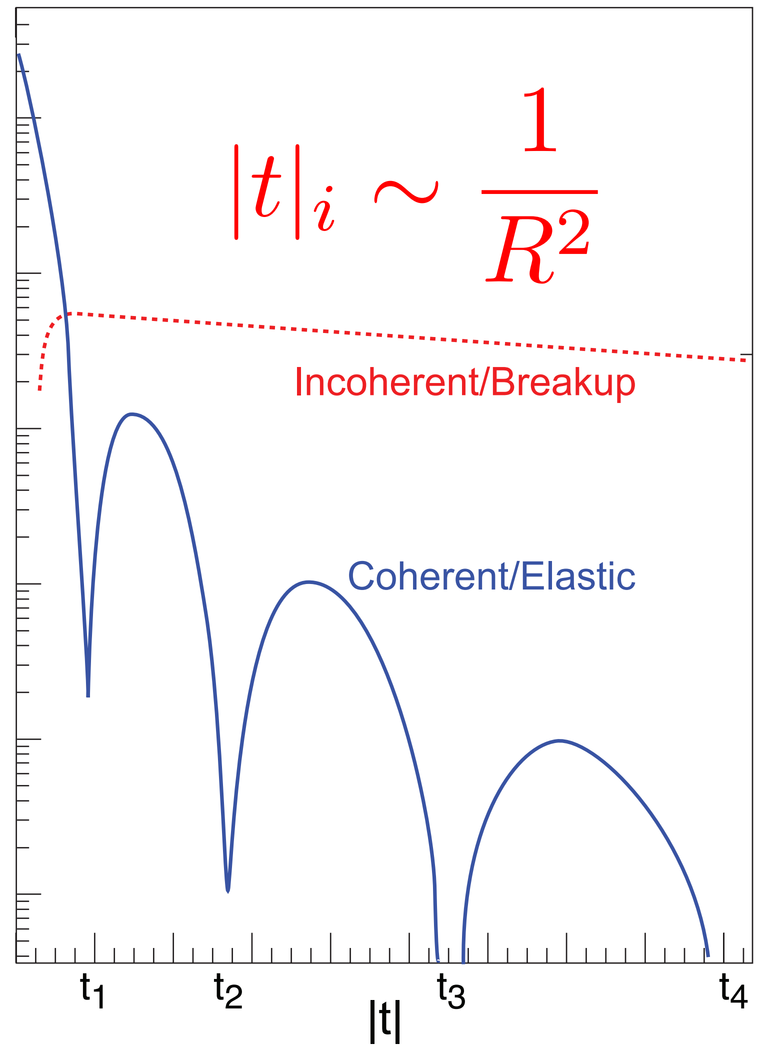

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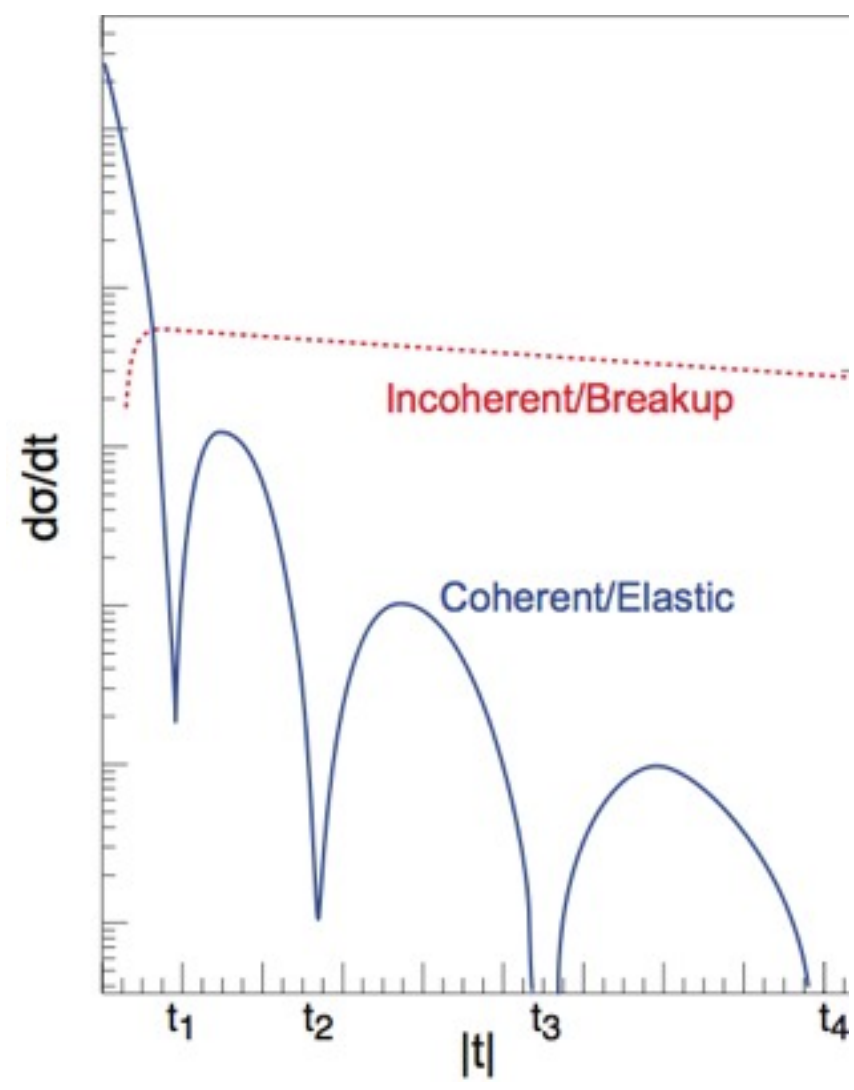
Diffraction at eRHIC

Difference in between *ep* & *eA*:
The Nucleus can break up
into colour neutral fragments!

When the nucleus breaks up, the scattering is called incoherent

When the nucleus stays intact, the scattering is called coherent



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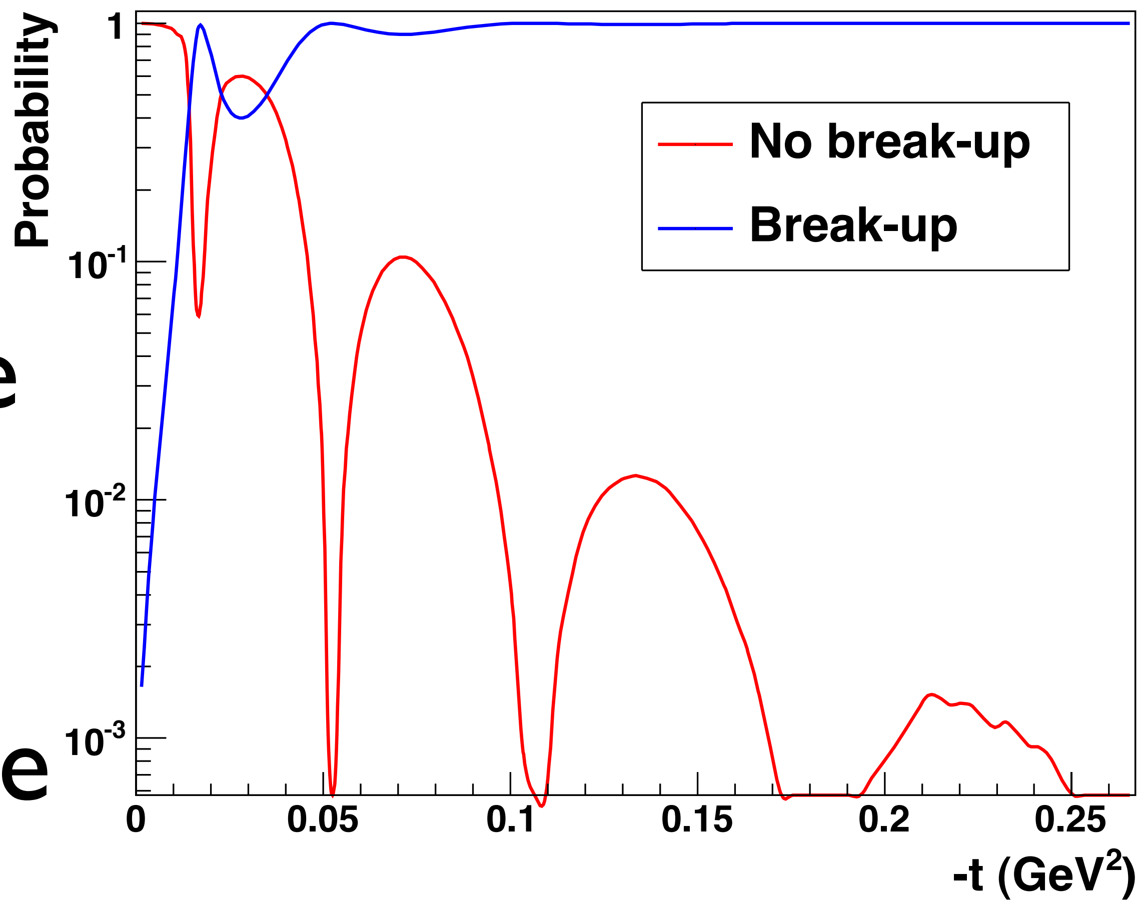

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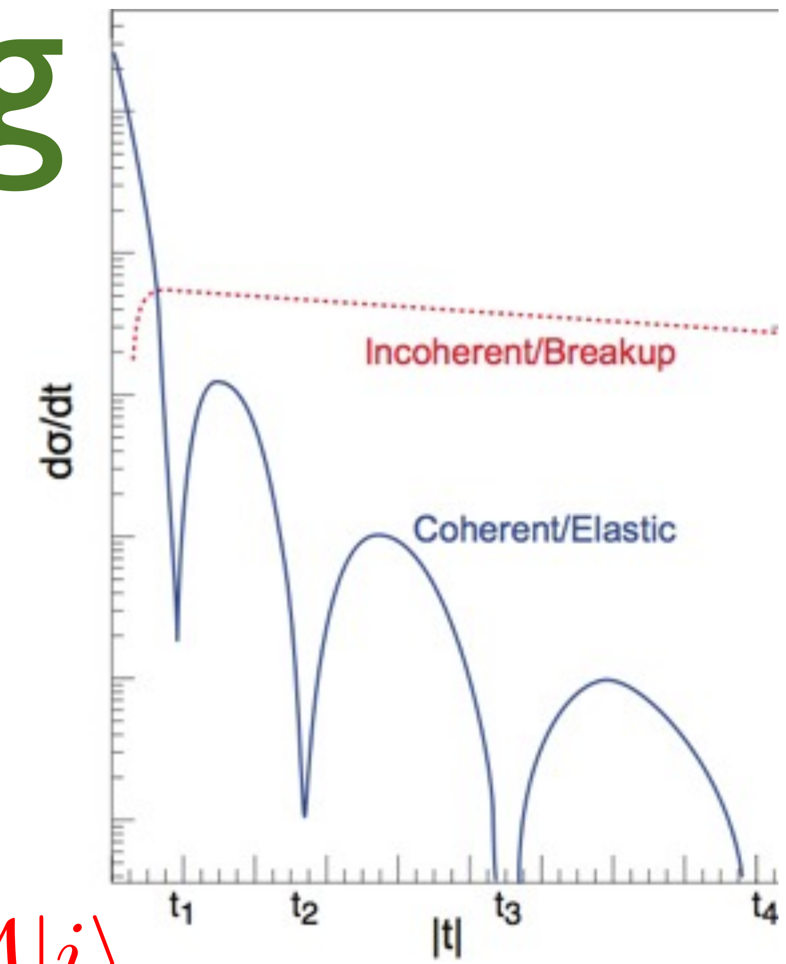
Incoherent Scattering



Good, Walker:

Nucleus dissociates ($f \neq i$):

$$\sigma_{\text{incoherent}} \propto \sum_{f\neq i} \langle i|\mathcal{A}|f\rangle^{\dagger} \langle f|\mathcal{A}|i\rangle$$

complete set

$$= \sum_{f} \langle i|\mathcal{A}|f\rangle^{\dagger} \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^{\dagger} \langle i|\mathcal{A}|i\rangle$$

$$= \left\langle i \left| |\mathcal{A}|^2 \right| i \right\rangle - \left|\langle i|\mathcal{A}|i\rangle\right|^2 = \left\langle |\mathcal{A}|^2 \right\rangle - \left|\langle \mathcal{A}\rangle\right|^2$$

The incoherent CS is the variance of the amplitude!!

$$\frac{d\sigma_{\text{total}}}{dt} = \frac{1}{16\pi} \left\langle |\mathcal{A}|^2 \right\rangle \qquad \frac{d\sigma_{\text{coherent}}}{dt} = \frac{1}{16\pi} \left|\langle \mathcal{A}\rangle\right|^2$$

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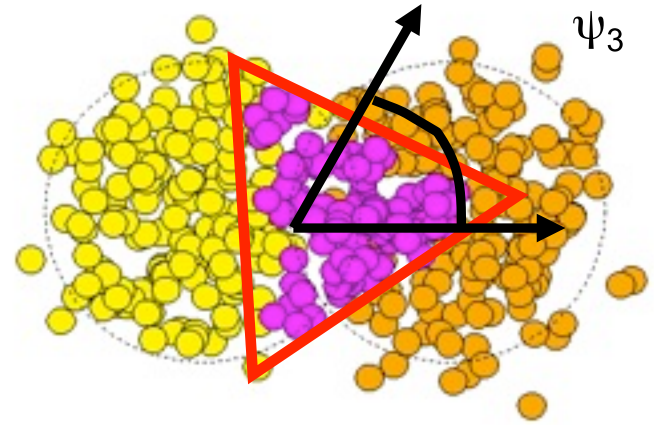
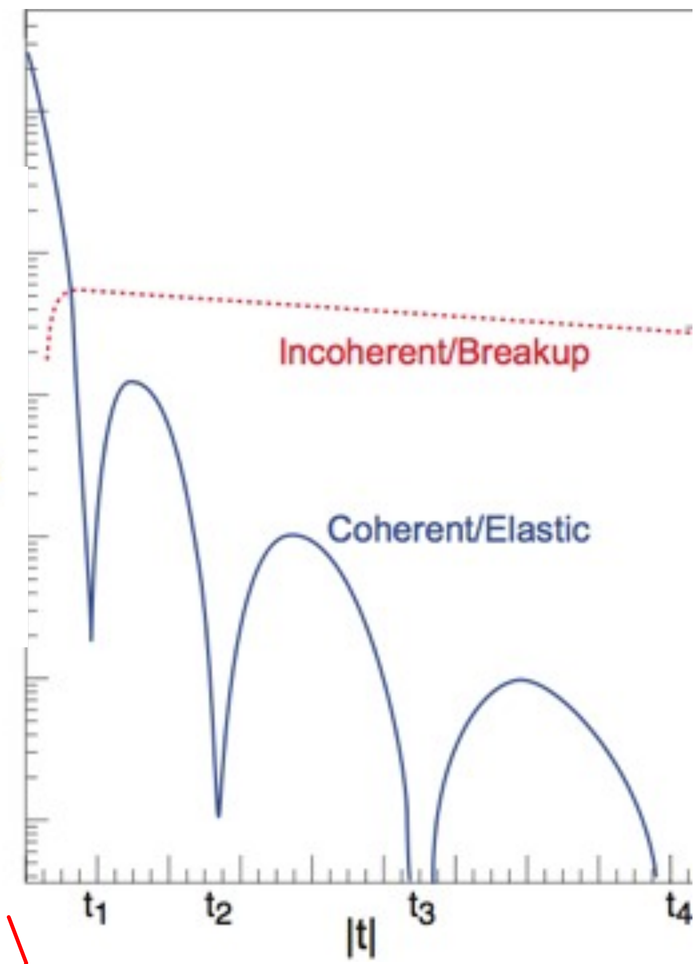
Incoherent Scattering





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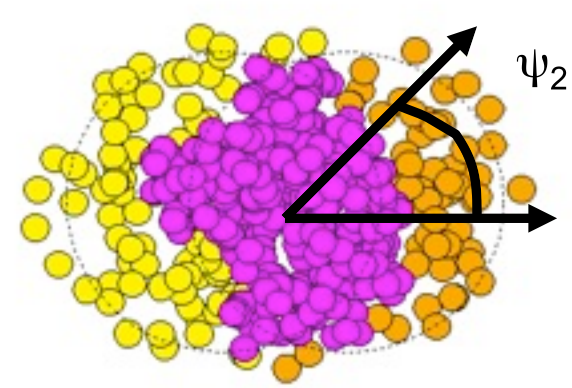
The incoherent CS is the variance of the amplitude!!

$$\frac{\mathrm{d}\sigma_{\text{total}}}{\mathrm{d}t} = \frac{1}{16\pi} \left\langle |\mathcal{A}|^2 \right\rangle$$

$$\frac{\mathrm{d}\sigma}{}$$



$$\mathcal{A}\rangle|^2$$

Why? Standard model of Heavy Ion Collisions

Our understanding of some fundamental properties of the Glasma, sQGP and **Hadron Gas** depend strongly on our knowledge of the initial state!

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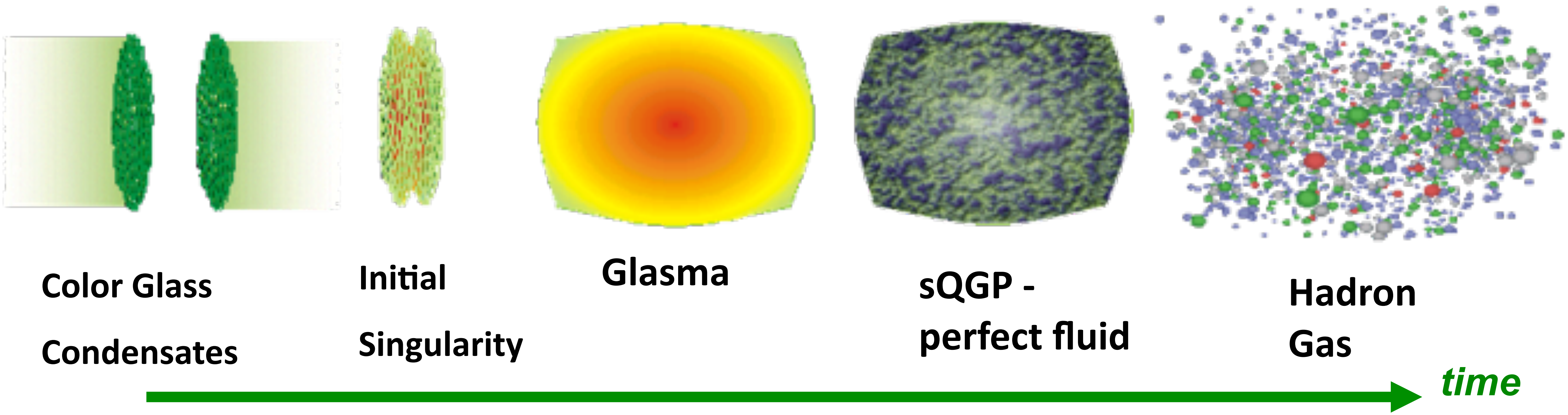

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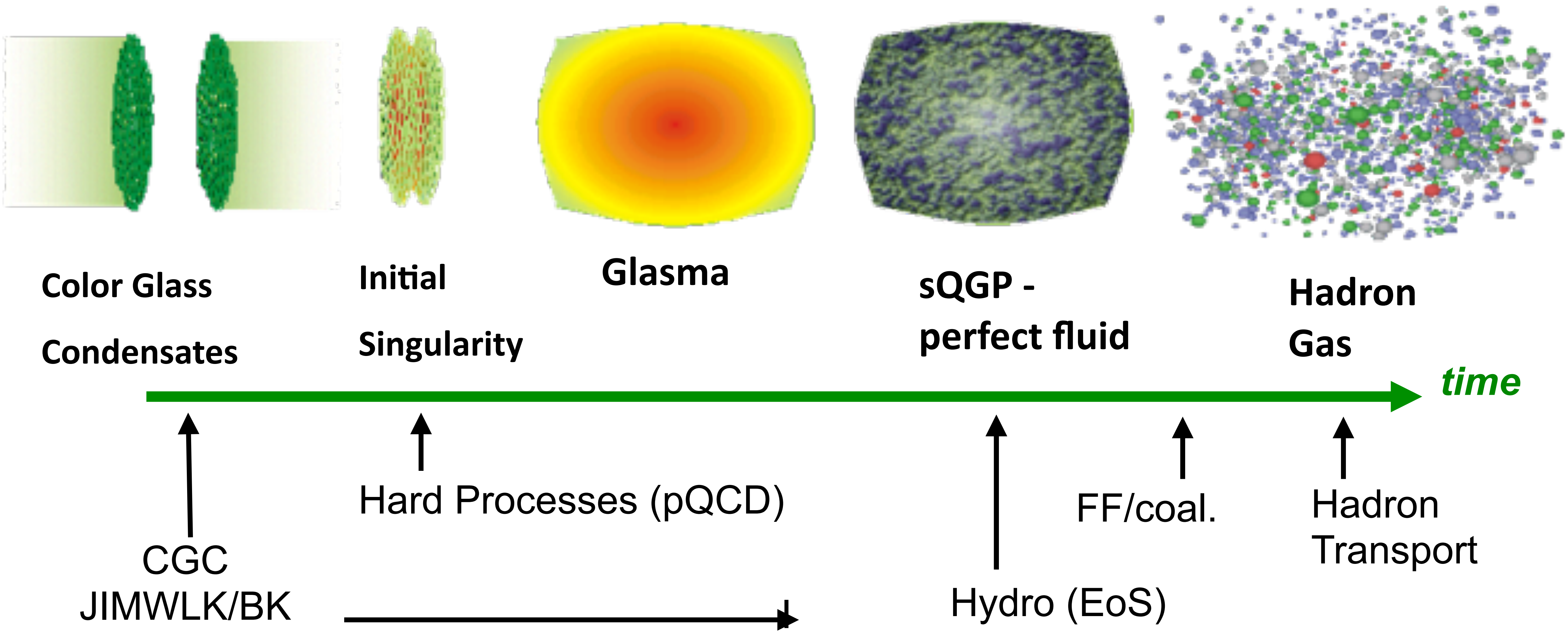

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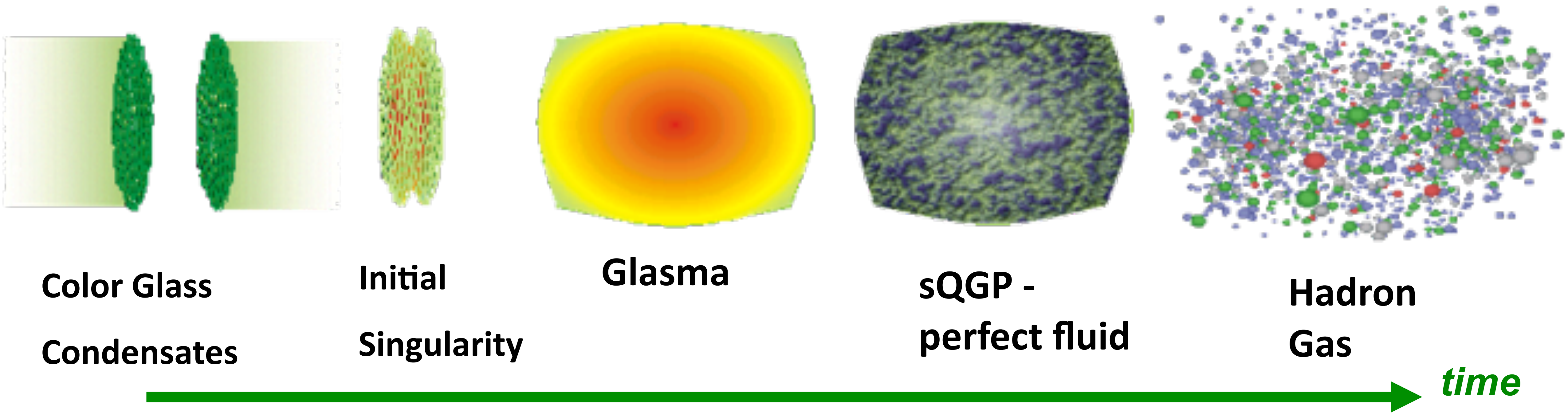

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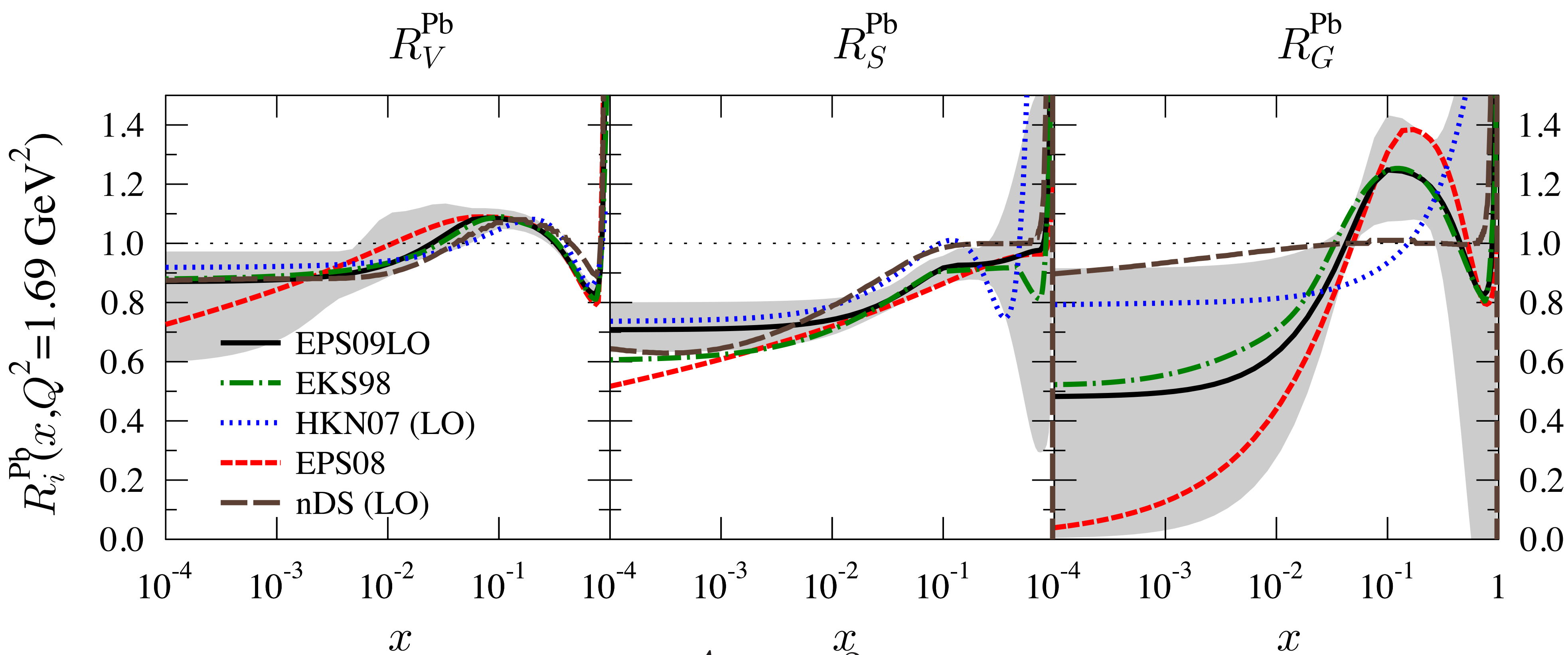
How well do we know the initial state?

Momentum density functions:

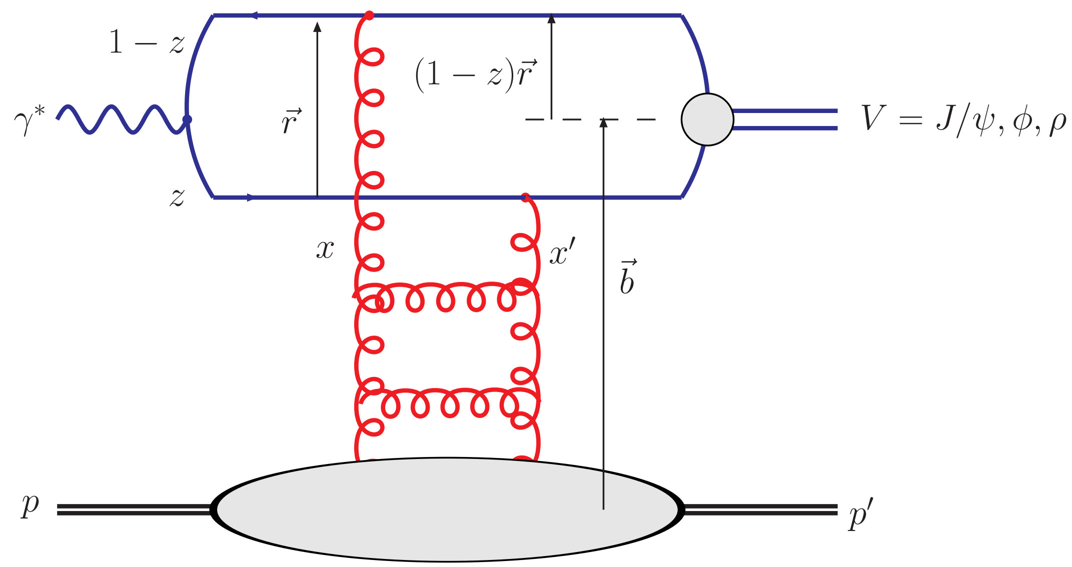


$$R^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{A f_i^{\mathrm{nucleon}}(x,Q^2)}, \qquad f_i = q, \bar{q}, g,$$

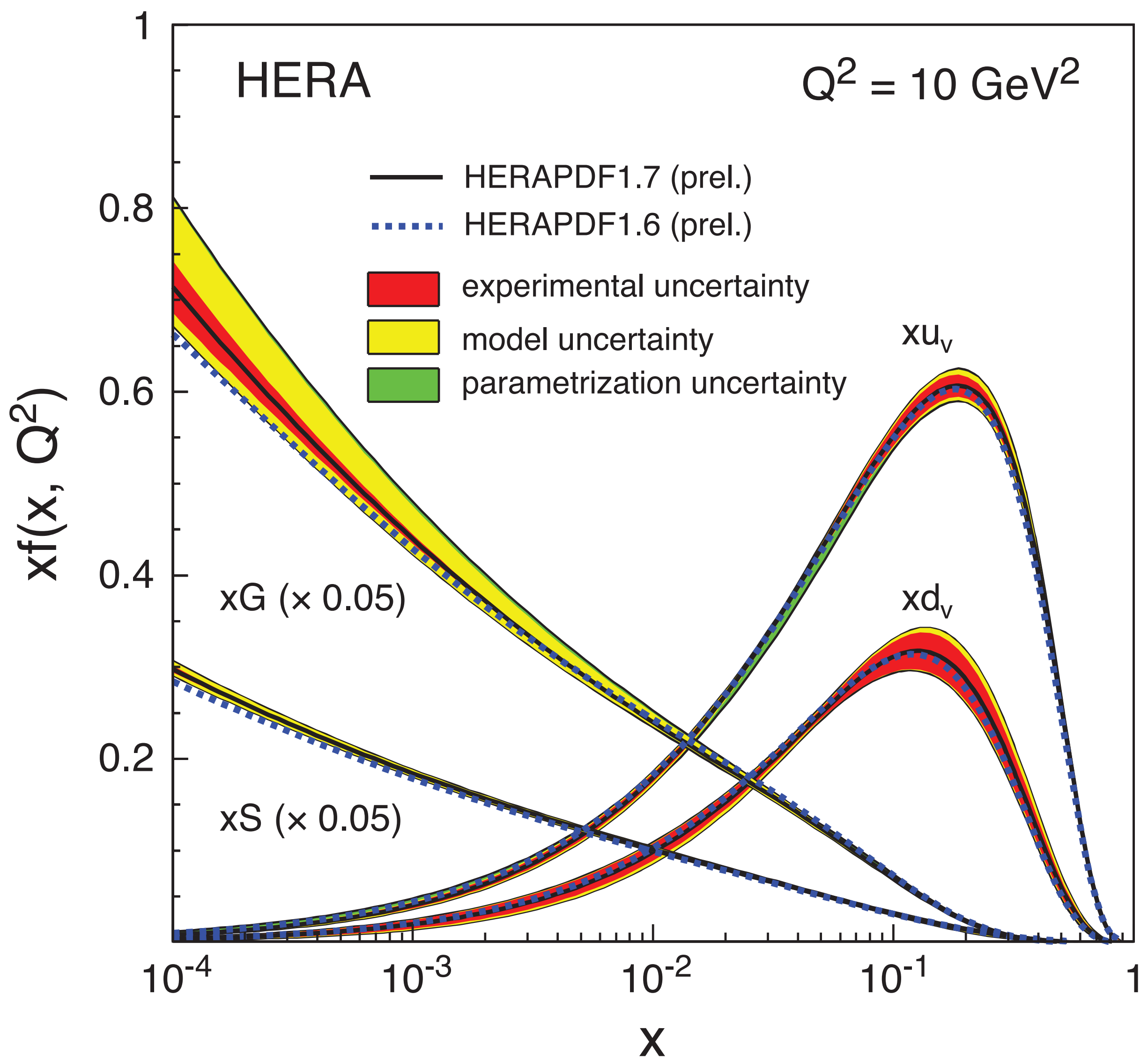
- PDFs in p are reasonable well under control for $10^{-4} < x < 0.3$
- PDFs in A less constraint (at low-x could hide higher twist effects)
- EMC (0.25 < x < 0.8) only at very high pT at RHIC
- Anti-shadowing (0.1 < x < 0.25)
- Shadowing (x < 0.1)

Why is diffraction so great?

Diffraction sensitive to gluon momentum distributions[2]:



$$\sigma \propto g(x,Q^2)^2$$



How does the gluon distribution saturate at small *x*?

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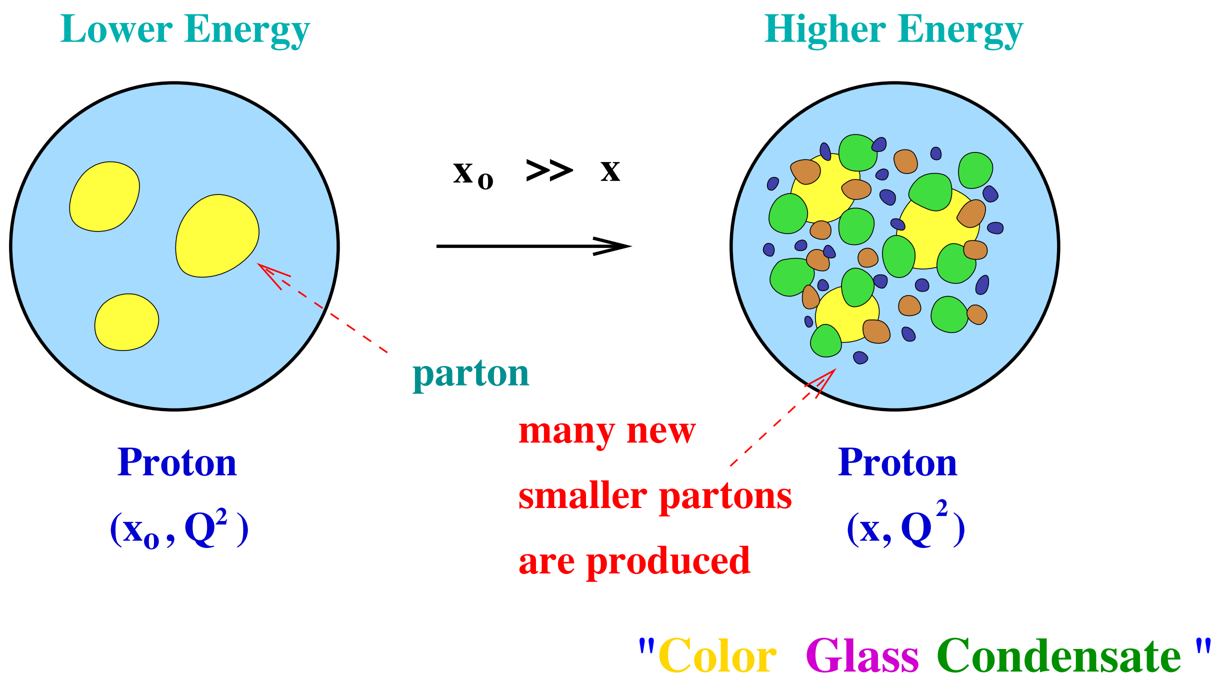
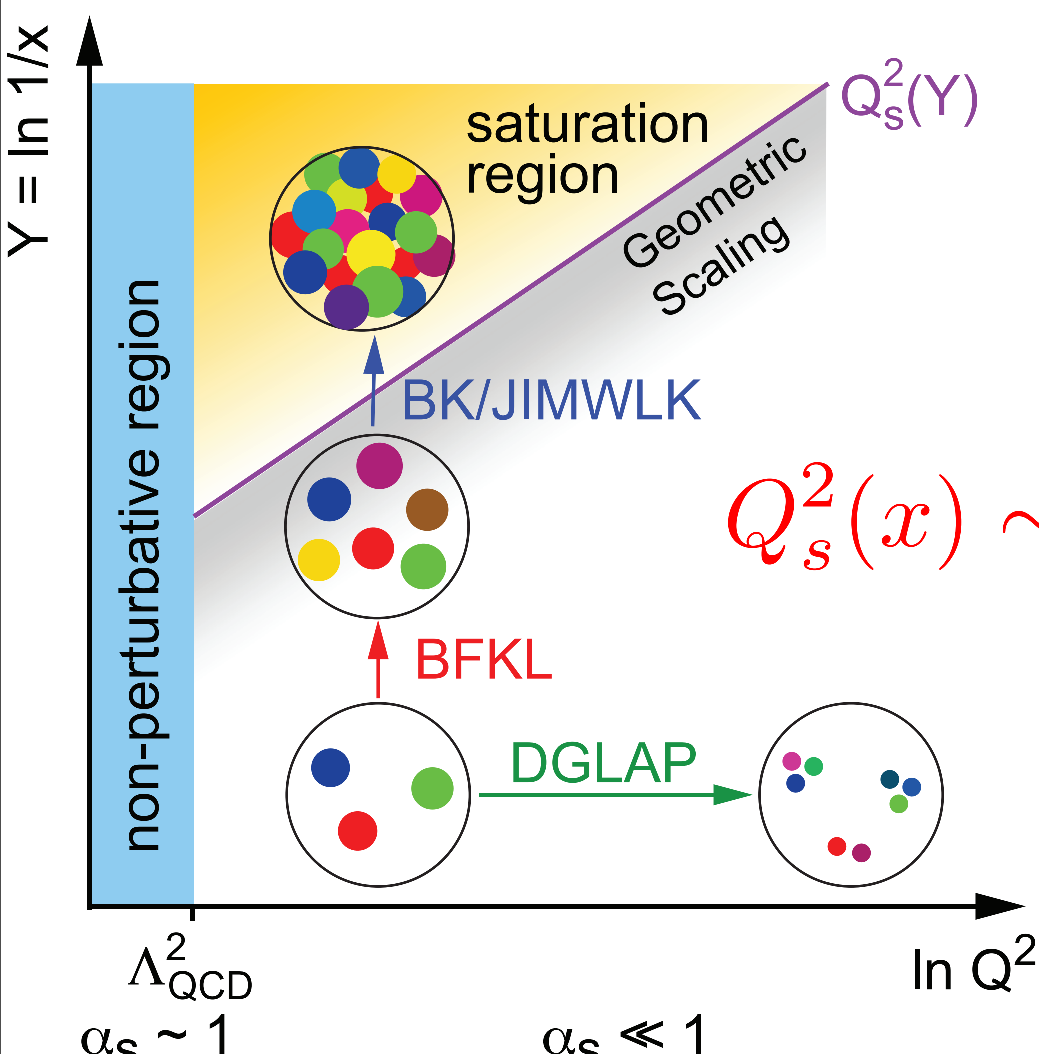
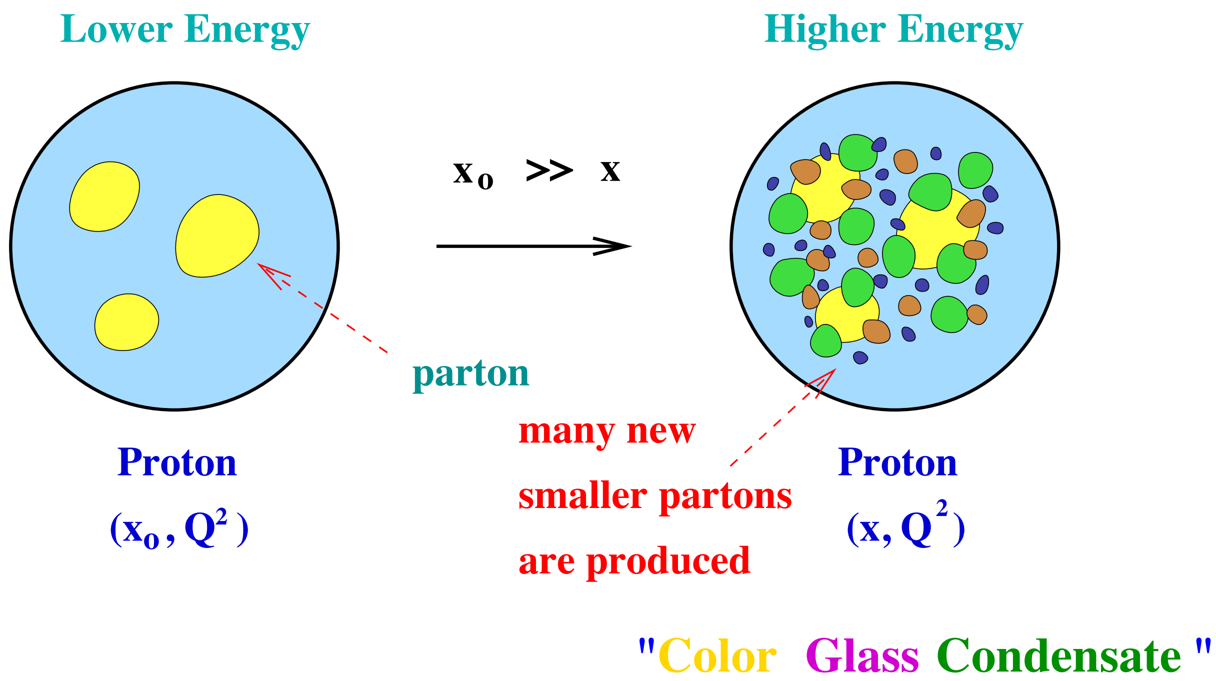
Saturation at eRHIC

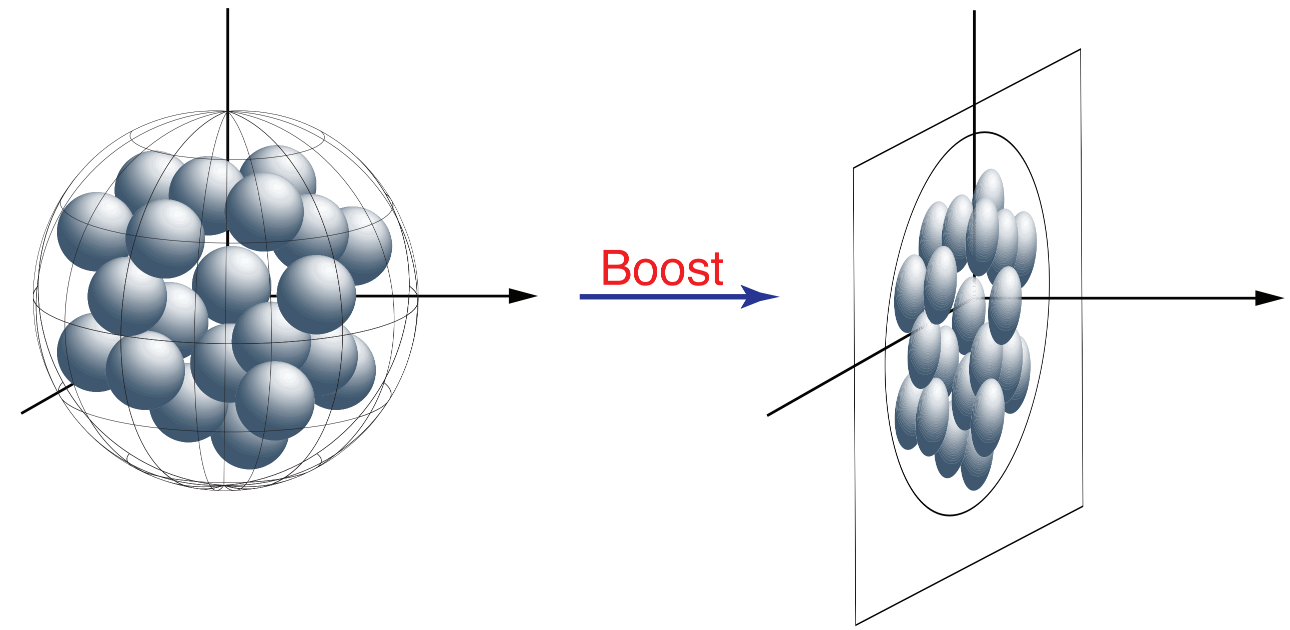


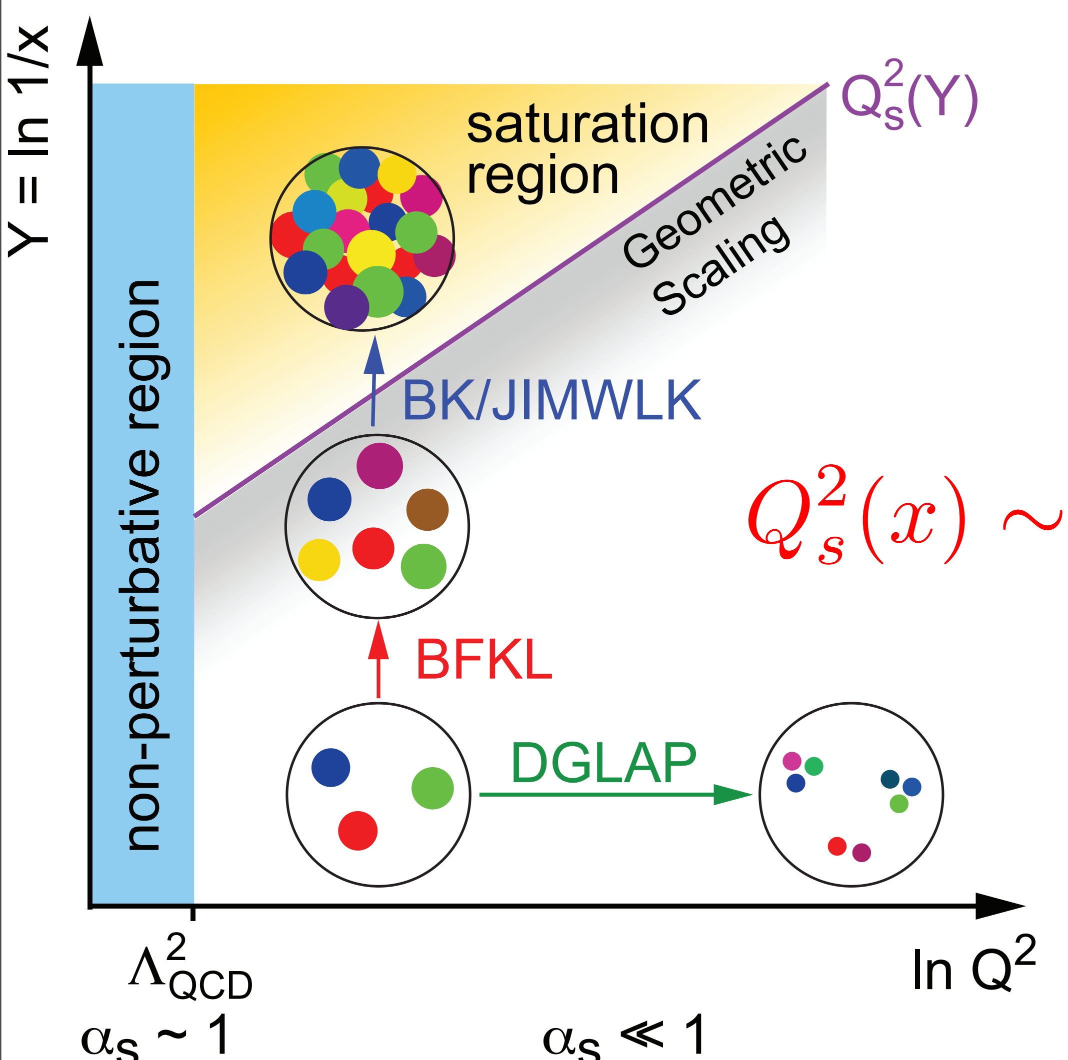


$$Q_s^2(x) \sim \left(\frac{1}{x}\right)^{\lambda}$$

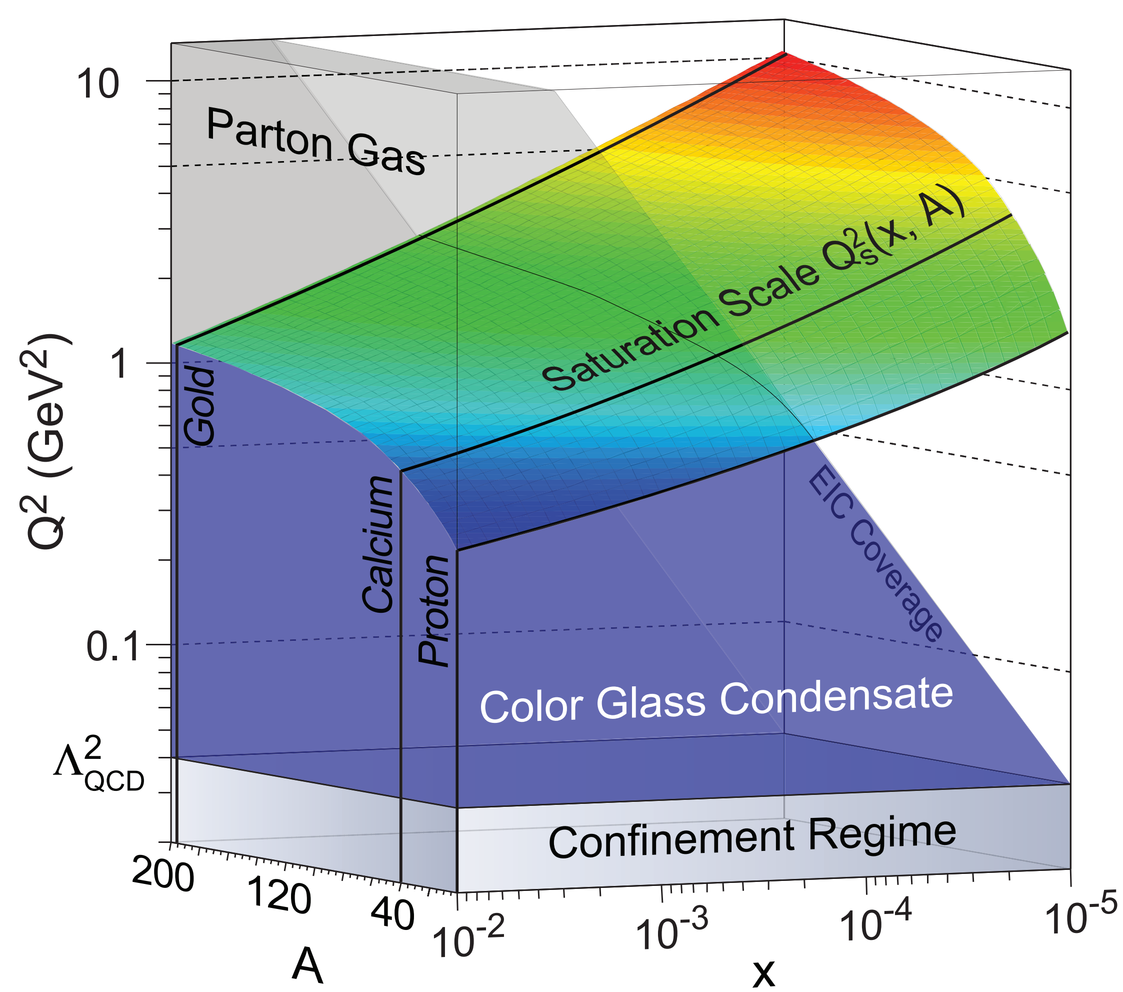
Saturation at eRHIC







$$Q_s^2(x) \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

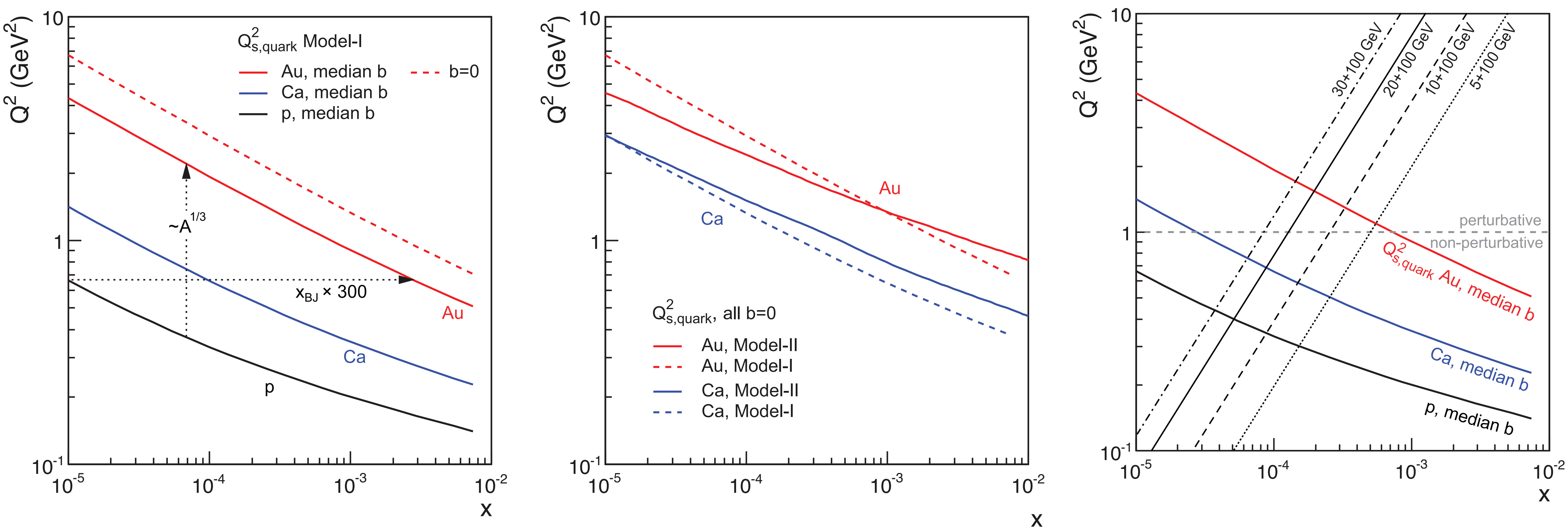


Saturation at eRHIC

Pocket formula:

$$Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$$

Gold: A=197, *x* 197 times smaller!



Model-I: bSat, Model-II: rcBK

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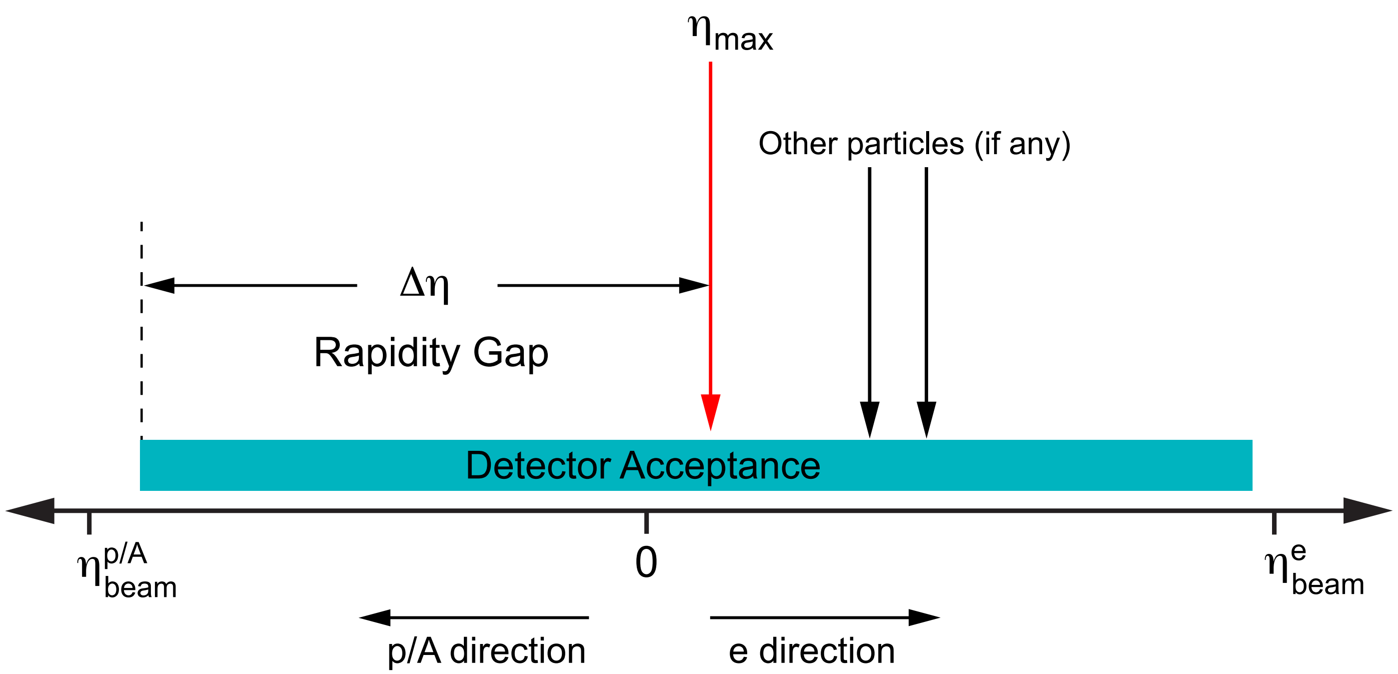
How to measure diffraction at eRHIC

Key eA measurements at eRHIC

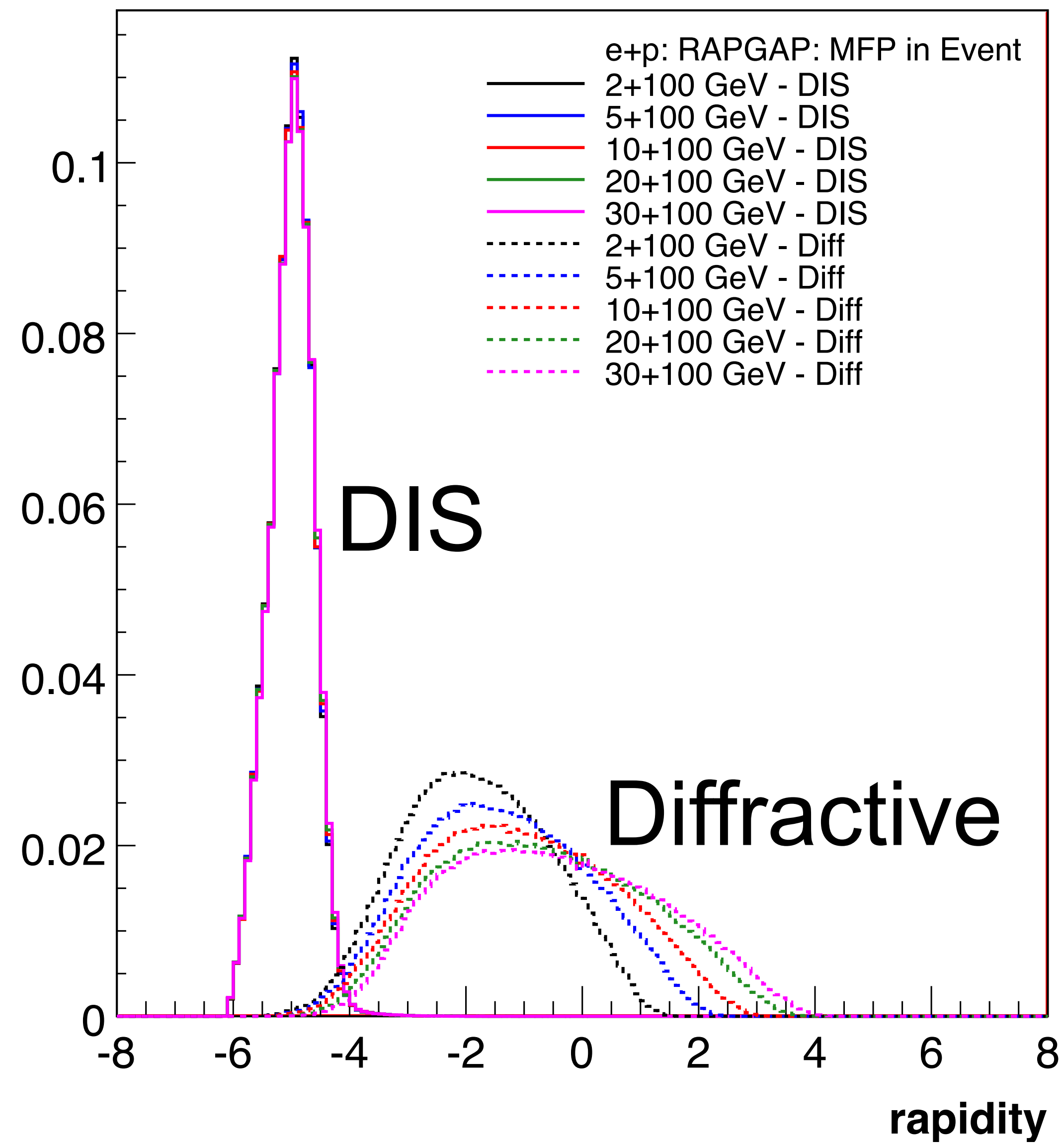
Deliverables	Observables	What we learn	Stage-I	Stage-II
Integrated gluon momentum distributions	$F_{2,L}$	Nuclear wave function; saturation	Gluons at $10^{-3} \lesssim x \lesssim 1$	Exploration of the saturation regime
k_T-dependent gluons; gluon correlations	Di-hadron correlations	Non-linear QCD evolution/universality; saturation scale Q_s	Onset of saturation; Q_s measurement	Nonlinear small-x evolution
Spatial gluon distributions; gluon correlations	Diffractive dissociation $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ vector mesons & DVCS $d\sigma/dt$, $d\sigma/dQ^2$	Nonlinear small-x evolution; saturation dynamics; black disk limit	saturation vs. non-saturation models	Spatial gluon distribution; Q_s vs centrality

Measuring Diffraction at eRHIC

- Identify Most Forward Going Particle (MFP)



Diffractive ρ^0 production at eRHIC: η of MFP



M. Lamont '10

Hermeticity requirement:

- needs just to detect presence
- does not need momentum or PID
- studies done at BNL: can achieve 1% contamination, 80% efficiency

Measuring $t=(p-p')^2$

$$\theta_{\min} = 0.08\mathrm{mrad}(10\sigma)$$
$$p = 100\ \mathrm{GeV}$$

For coherent diffraction one needs to measure the scattered ion.

Only possible if it is separated from the beamline detectors by an angle $\theta_{\min}$, which requires a momentum kick of at least:

$$p_t^{\min} \approx pA\theta_{\min}$$

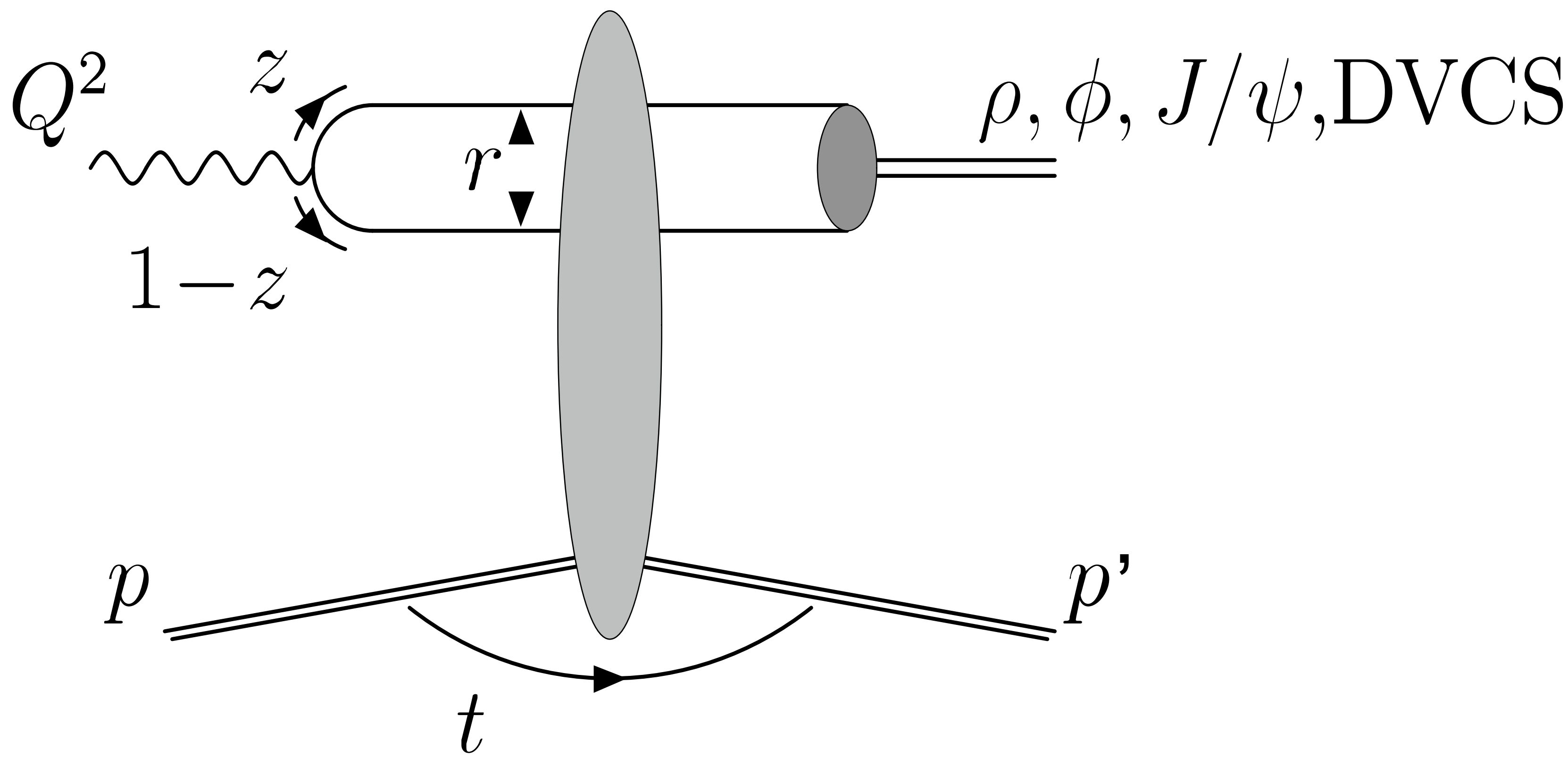
species (A)	p_T^{min} (GeV/c)
d (2)	0.02
Si (28)	0.22
Cu (64)	0.51
In (115)	0.92
Au (197)	1.58
U (238)	1.90

For incoherent diffraction all beam remnants have to be measured for *t* to be reconstructed.

Both cases impossible - Need exclusive diffraction!

Exclusive Vector Meson Production

- Golden channel: e + A → e' + VM + A'
  - $t = (P_A - P_{A'})^2 = (P_{VM} + P_{e'} - P_e)^2$
  - photoproduction ($Q^2 \approx 0$): $t \approx p^2_{T,VM}$
  - moderate Q^2: need p_T of e'
  - Issues:
    - transverse spread of the beam (distorts small t) ⇒ requires beam cooling
    - detect incoherent events ⇒ detect nuclear breakup



Detecting Nuclear Breakup

- Detecting **all** fragments $p_{A'} = \sum p_n + \sum p_p + \sum p_d + \sum p_\alpha$ ... not possible
- Focus on n emission
  - Zero-Degree Calorimeter
  - Requires careful design of IR
- Additional measurements:
  - Fragments via Roman Pots
  - γ via EMC

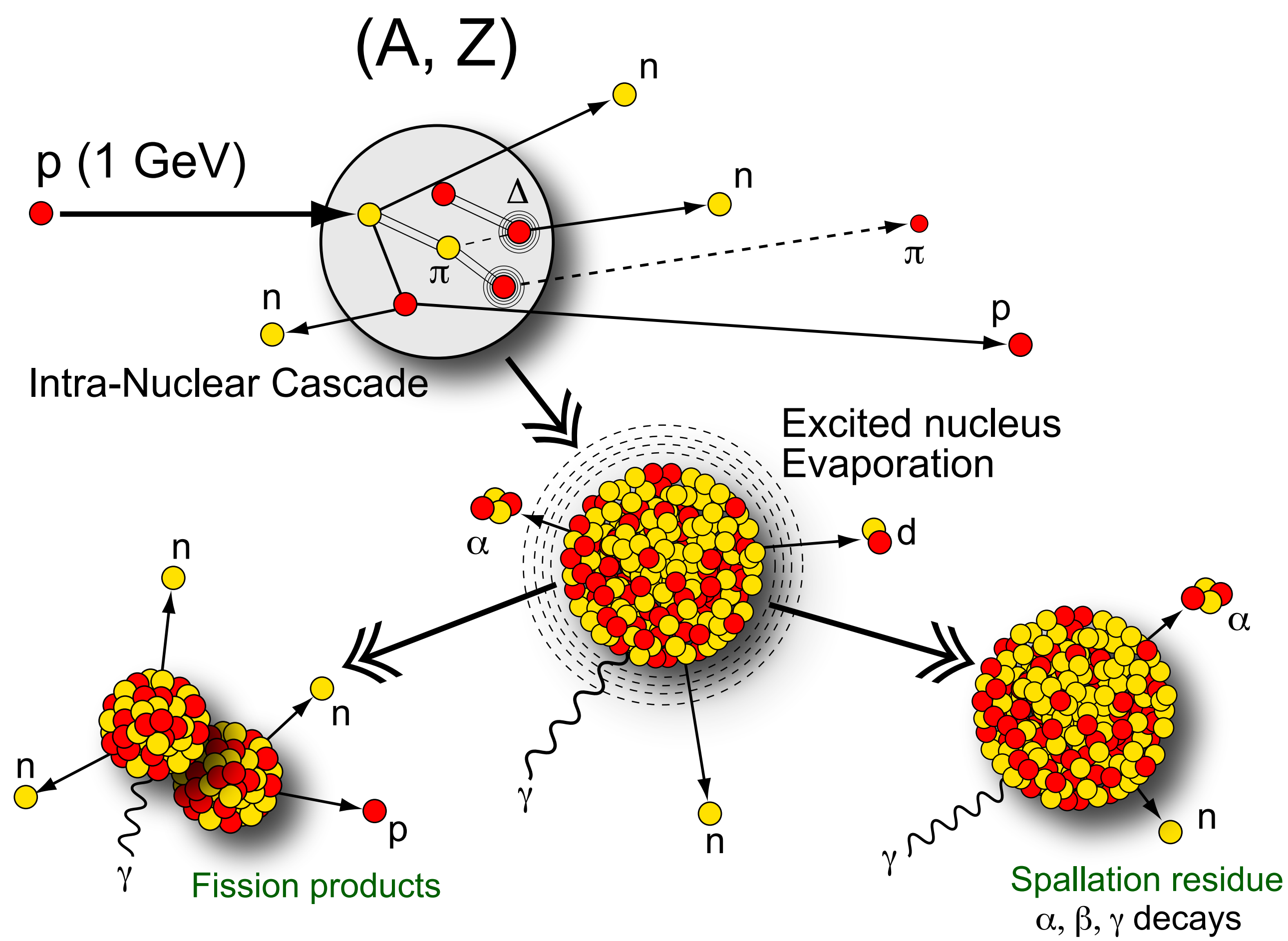
Traditional modeling done in pA:

Intra-Nuclear Cascade

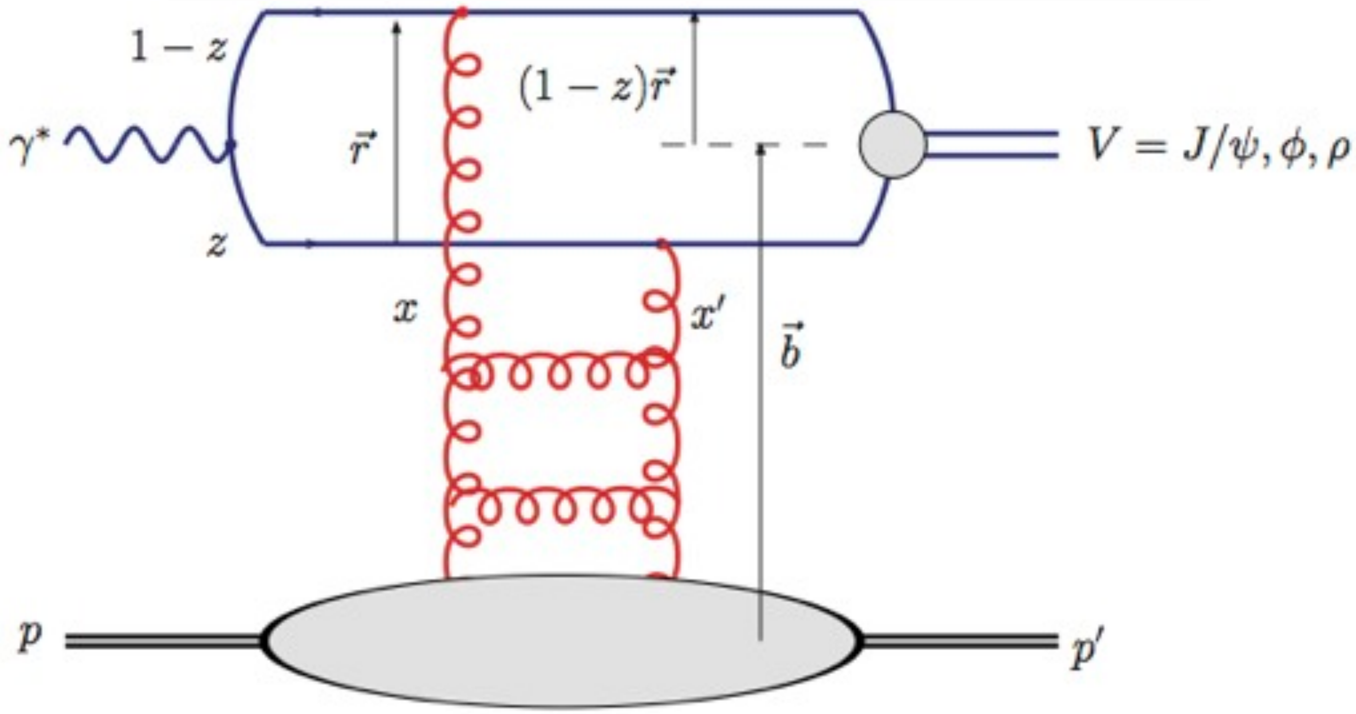
- Particle production
- Remnant Nucleus (A, Z, E*, ...)
- ISABEL, INCL4

De-Excitation

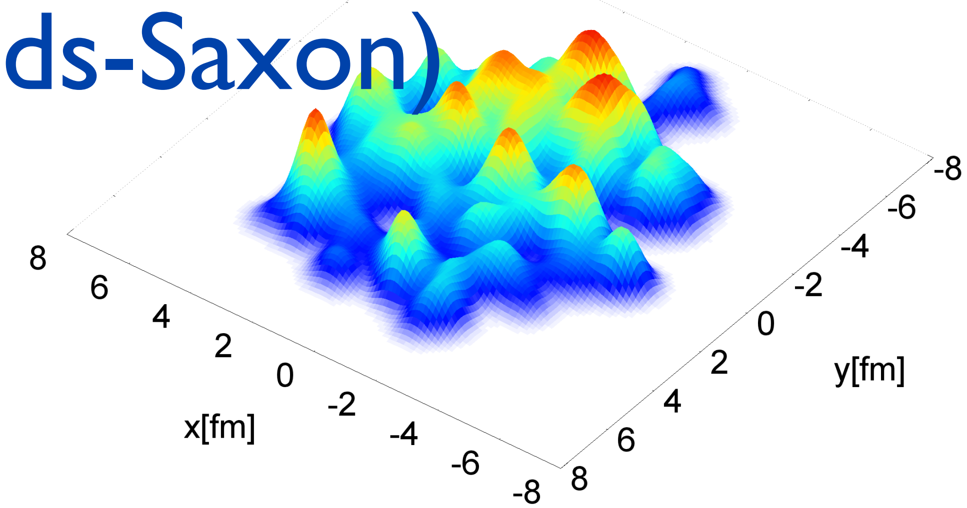
- Evaporation
- Fission
- Residual Nuclei
- Gemini++, SMM, ABLA (all no γ)

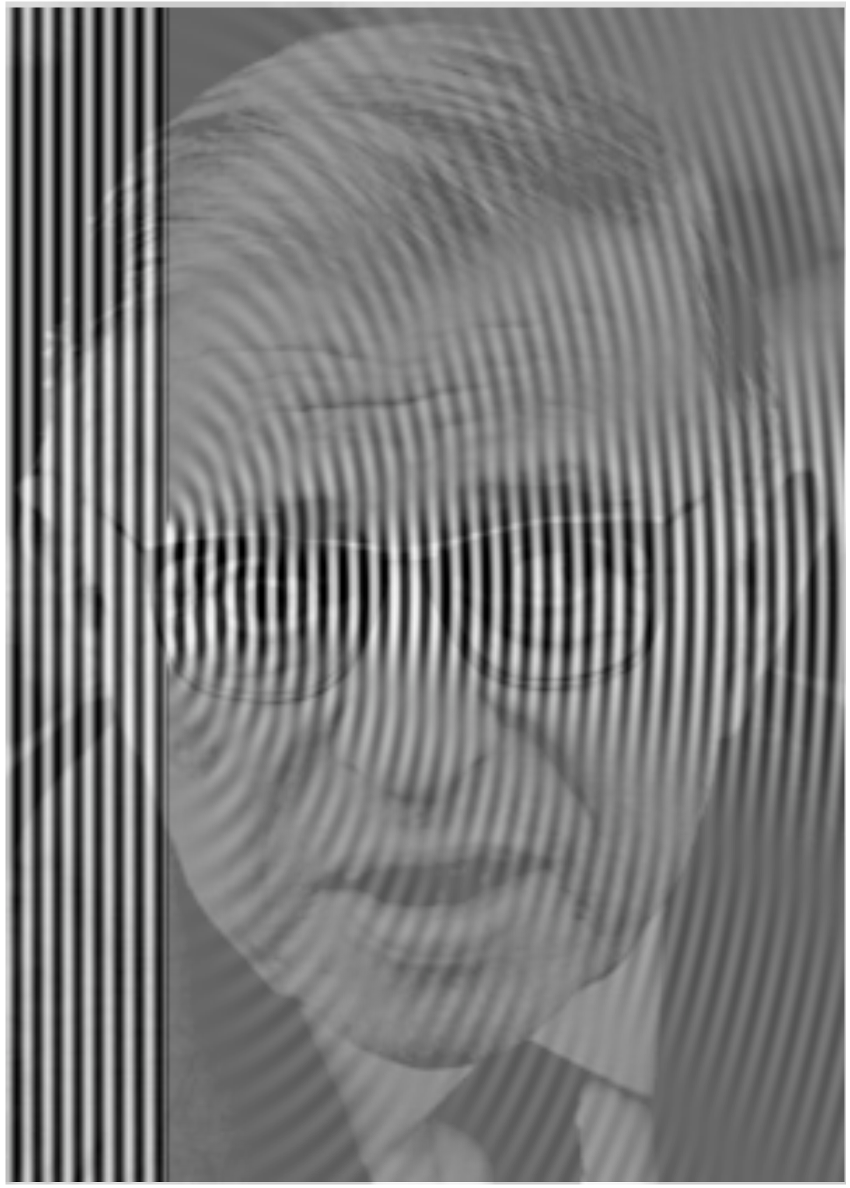


eRHIC predictions: Exclusive diffraction Sartre



Glauber (Woods-Saxon)





T. Ullrich & T.T.

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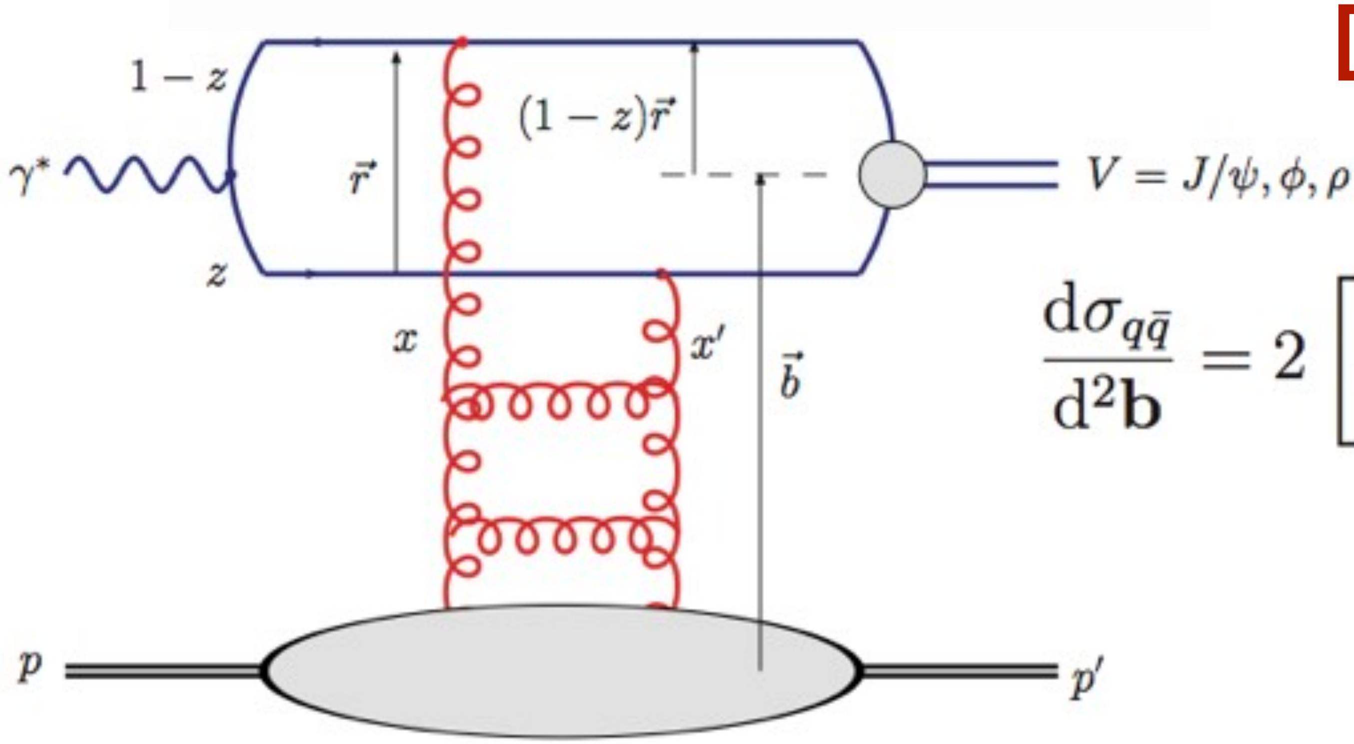
eRHIC predictions: Exclusive diffraction Sartre

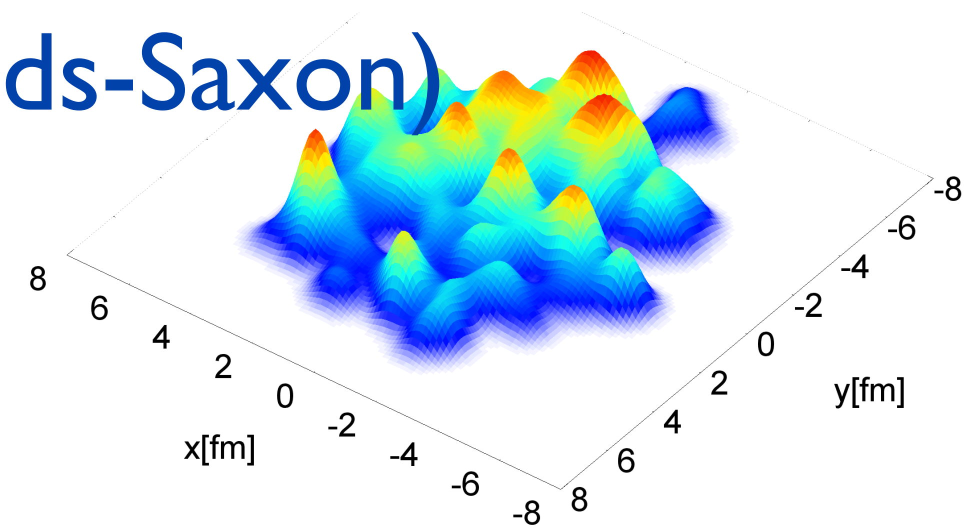


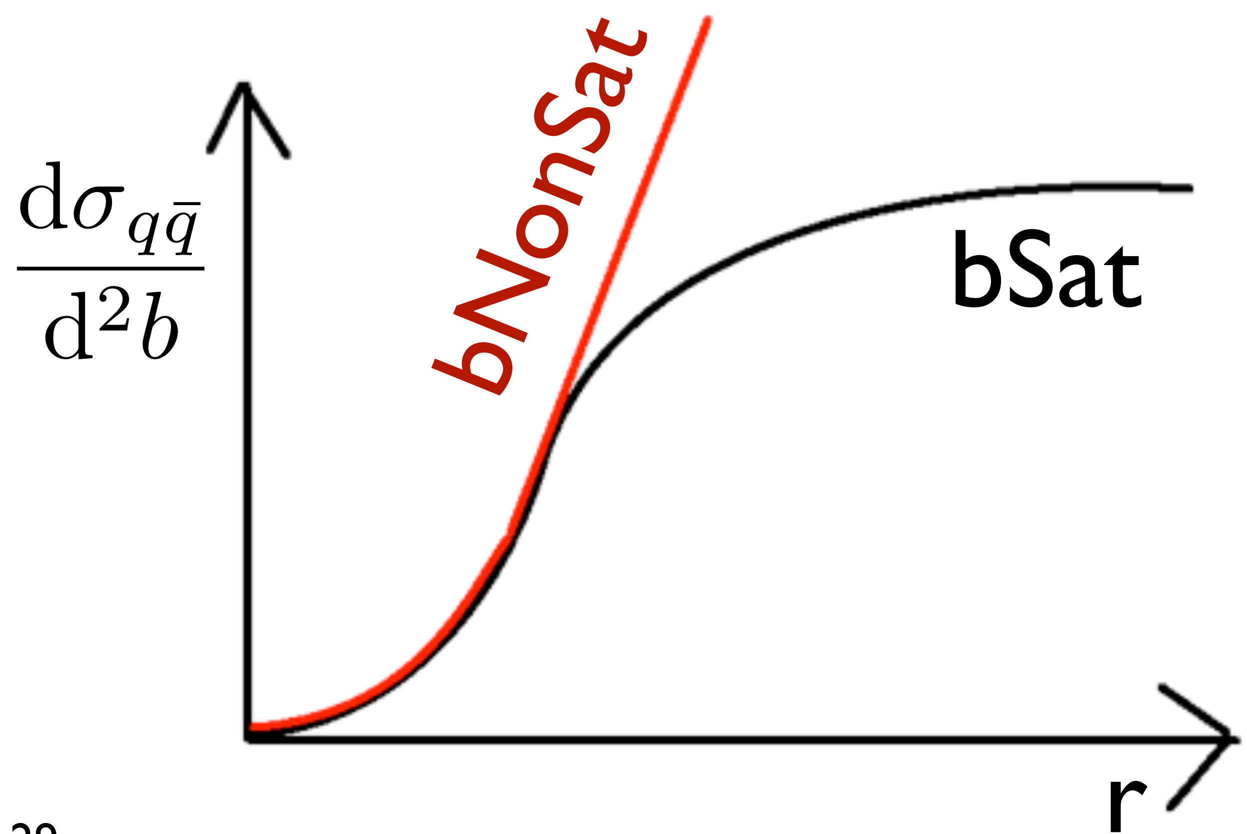
Dipole model with Glauber
bSat and bNonSat

$$\frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}} = 2\left[1-\exp\left(-\frac{\pi^2}{2N_c}r^2\alpha_s(\mu^2)xg(x,\mu^2)T(b)\right)\right]$$

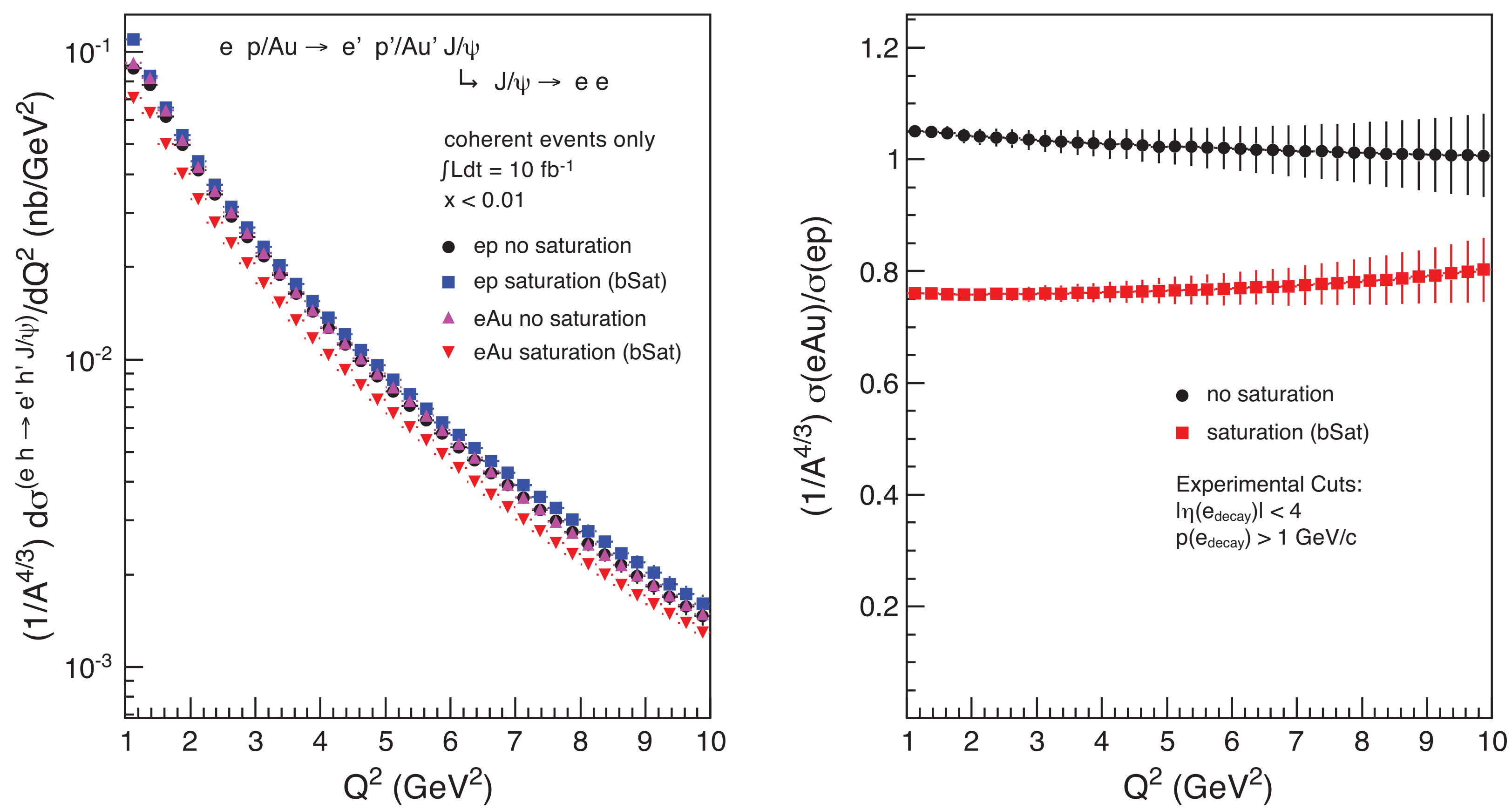
$$\frac{\pi^2}{N_C}r^2\alpha_s(\mu^2)xg(x,\mu^2)\sum_{i=1}^{A}T(|\mathbf{b}-\mathbf{b}_i|)$$

Glauber
(Woods-Saxon)





eRHIC predictions: Exclusive diffraction Sartre



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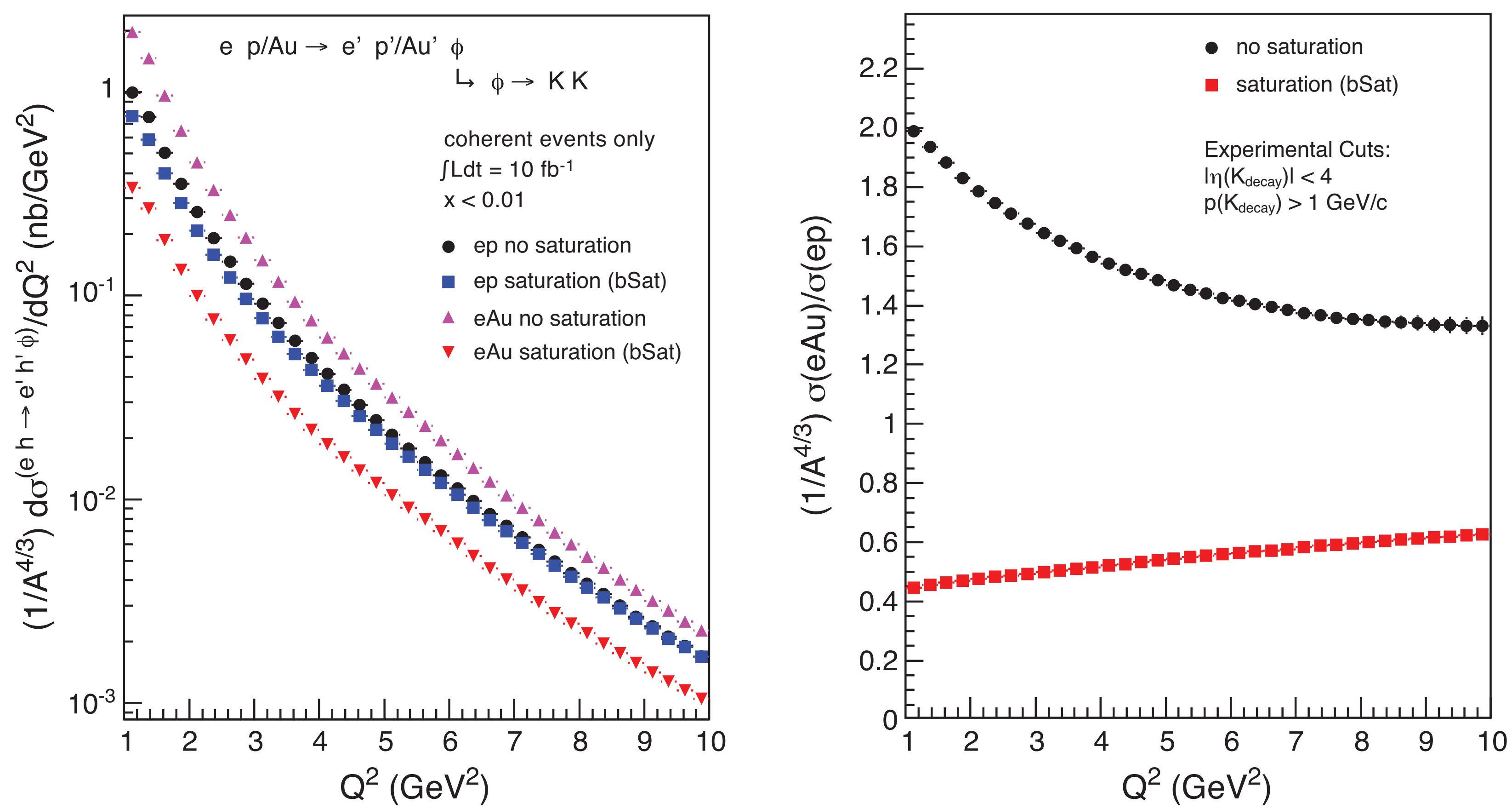
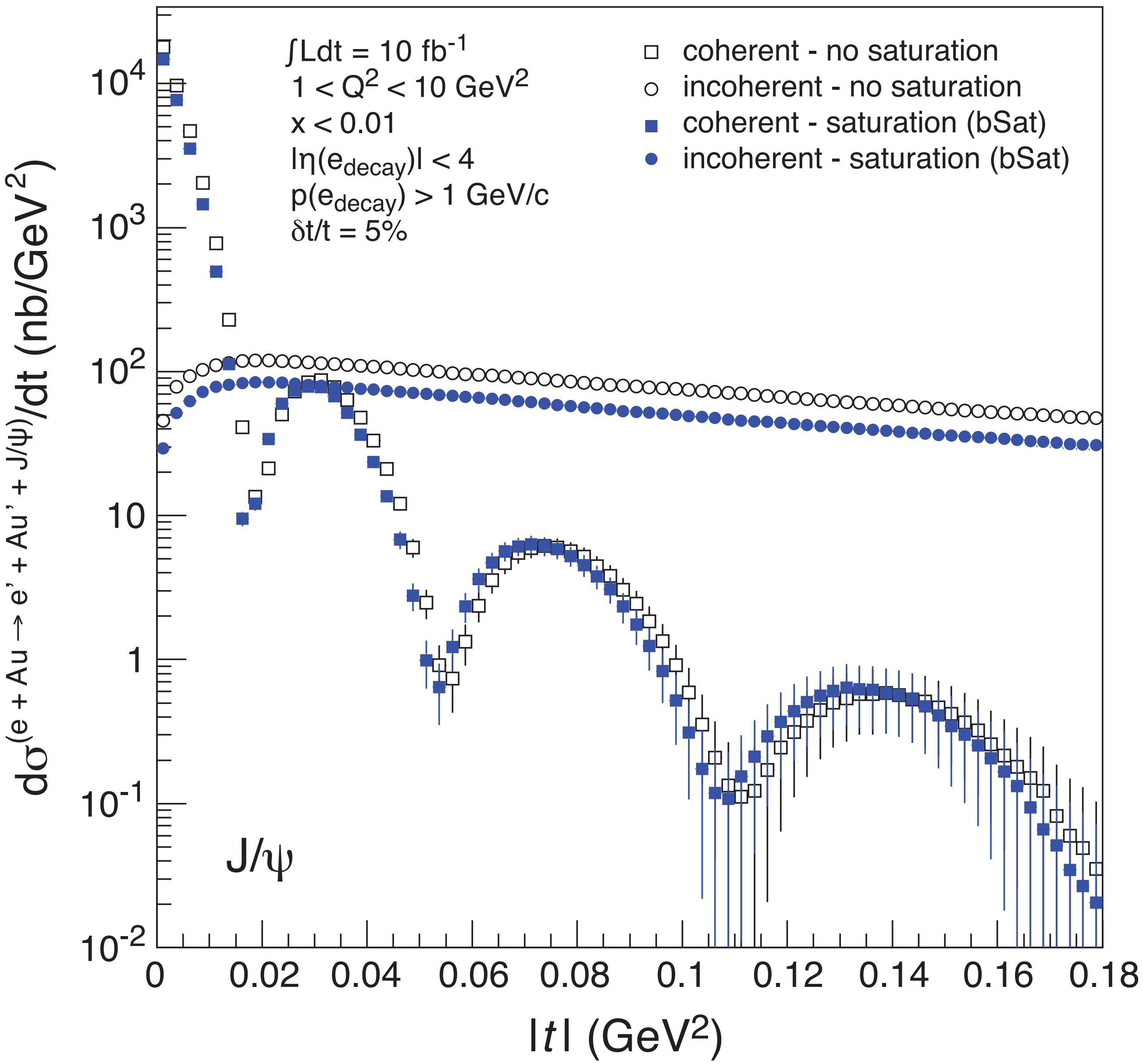
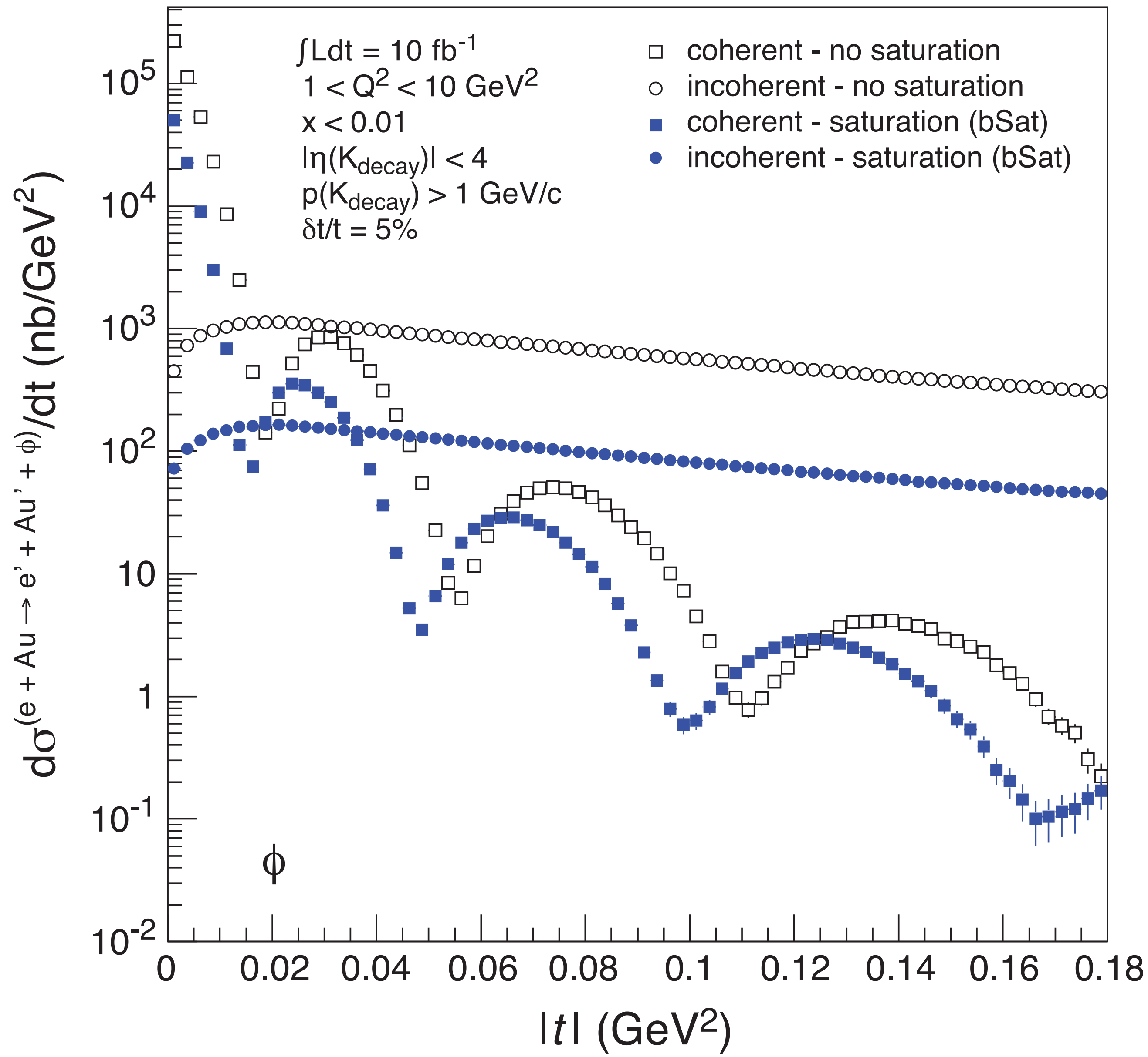
eRHIC predictions: Exclusive diffraction Sartre

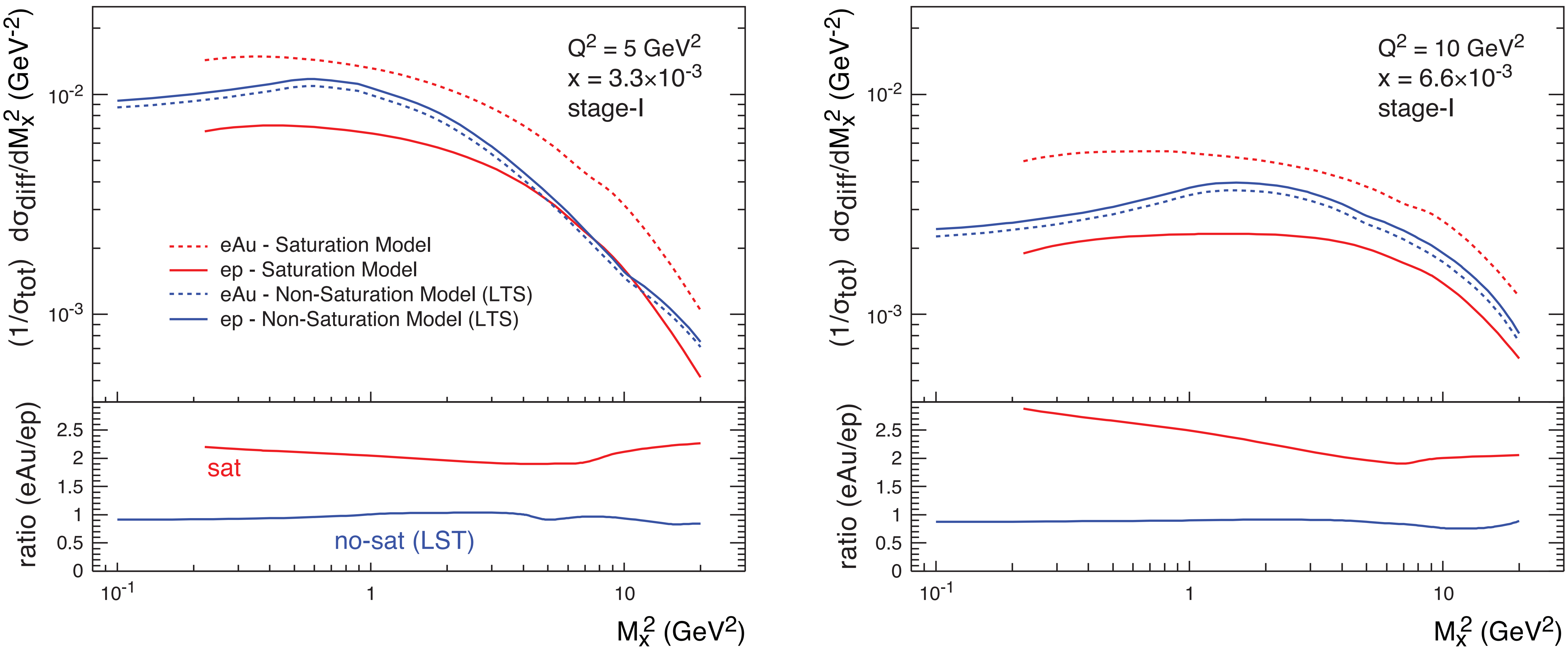


eRHIC predictions: Exclusive diffraction Sartre



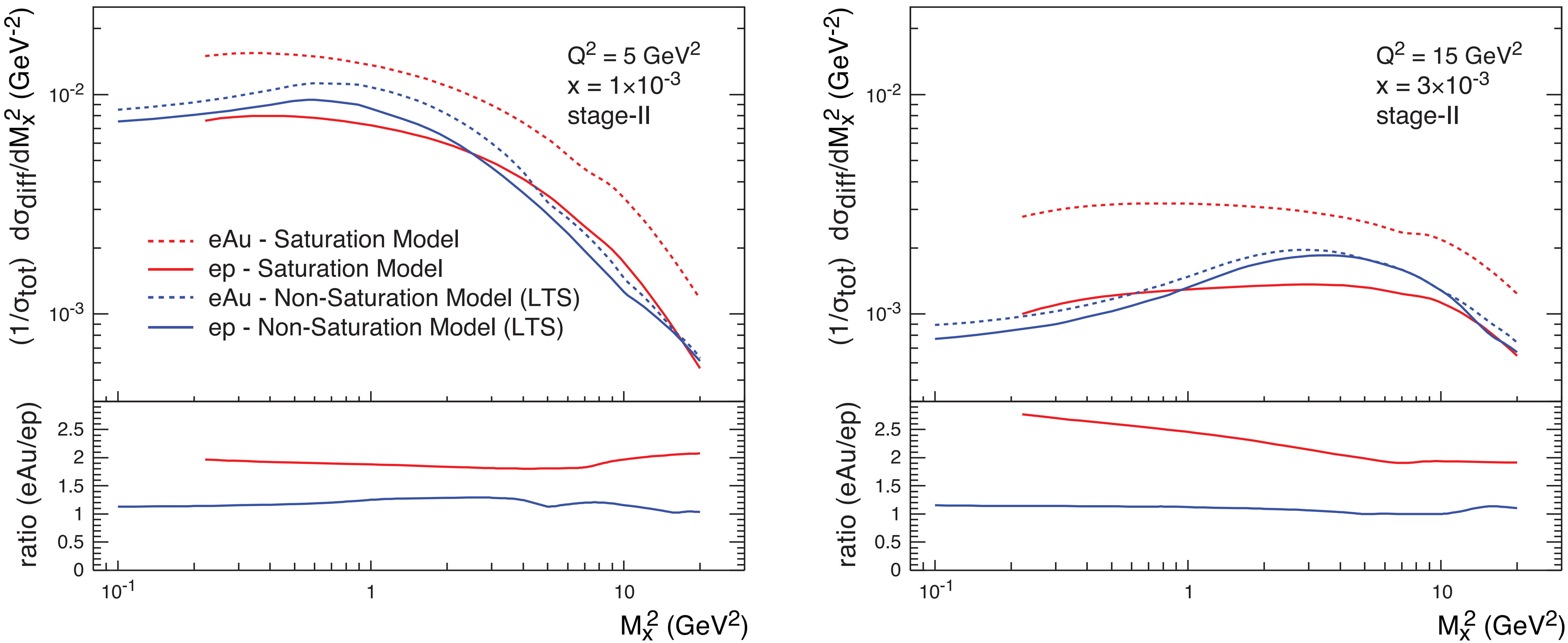


eRHIC predictions: Inclusive diffraction



Stage I

eRHIC predictions: Inclusive diffraction



Stage II

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Summary

To understand many properties at of heavy ion collision one must have a detailed understanding of the initial conditions of the ions.

eRHIC is a perfect environment to measure the intial condition at high precision.

eRHIC will open up a new regime for saturated QCD.

eRHIC is an ultra high resolution femtoscope!